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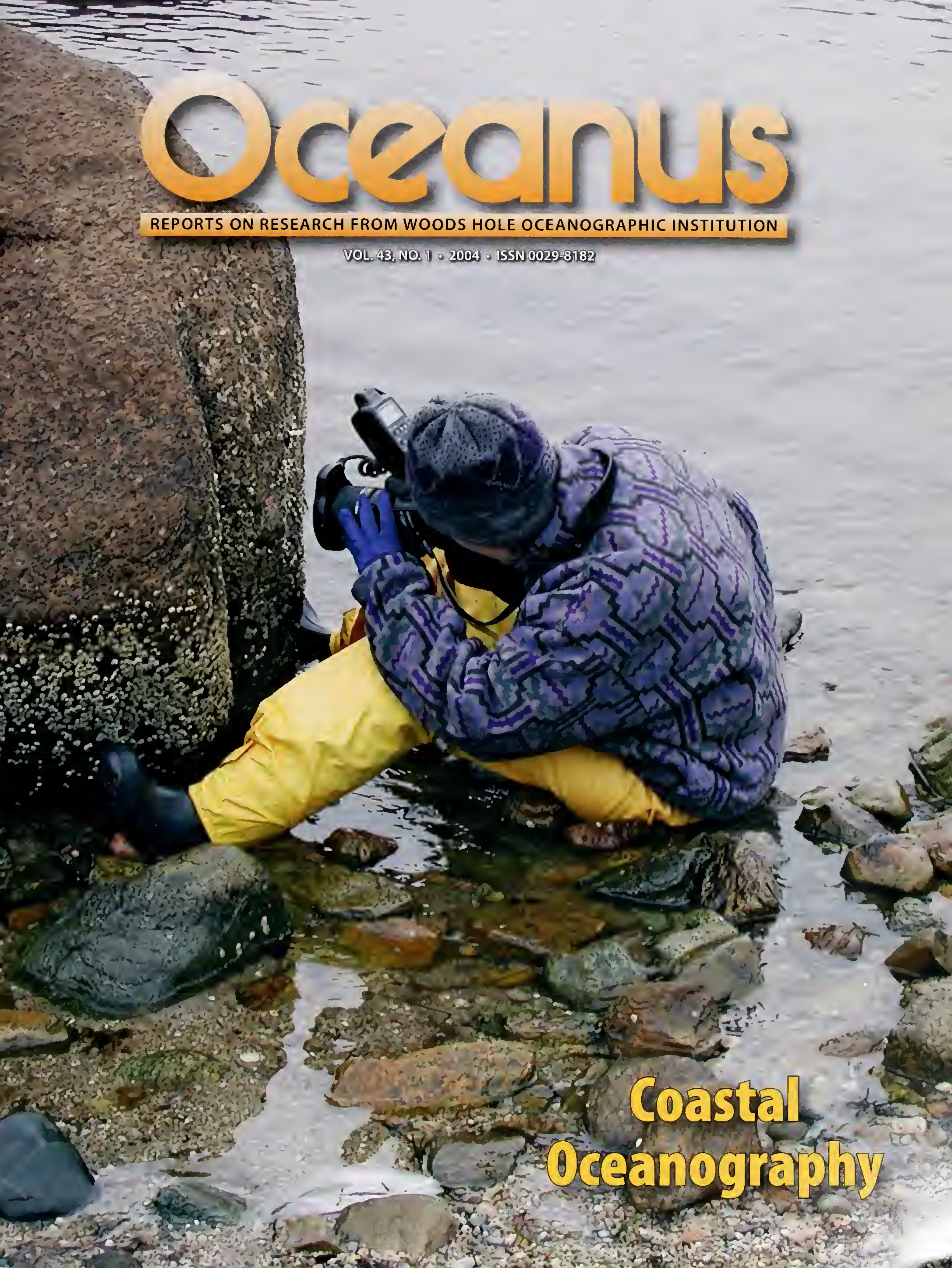

Coastal Oceanography

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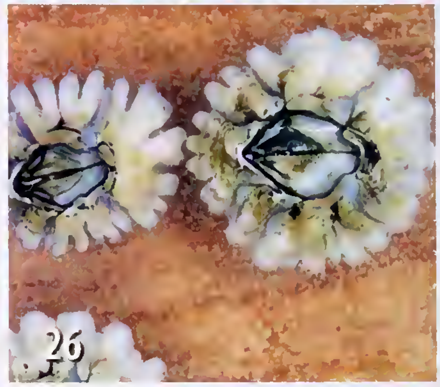

FRONT COVER: Tracy Pugh, a former WHOI research assistant, records the growth of barnacles in Buzzards Bay on Cape Cod, Mass. Photo by Jesús Pineda, WHOI Biology Department.

BACK COVER: The high-speed coastal research vessel *Tioga* departs Woods Hole for a day trip of testing oceanographic equipment. Research Associate Marshall Swartz of the Physical Oceanography Department visually inspects a conductivity-temperature-depth profiler (black bottles) that will be used to study the Hudson River estuary. On the fantail, the yellow robotic vehicle SeaBED awaits tests of navigation and imaging systems for underwater surveys on the continental shelf. Photo by Tom Kleindinst, WHOI Graphic Services.

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Strategic Waters:

Tapping coastal ocean resources

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

EDITOR: Mike Carlowicz
OCEAN INSTITUTE SERIES EDITOR: Lonny Lippsett
CONTRIBUTING EDITORS: Kate Madin, Amy E. Nevala, and Mildred Teal
DESIGNER: Jim Canavan, WHOI Graphic Services
CONTRIBUTING DESIGNERS: Katherine Joyce and Jeannine Pires
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The Coastal Ocean

At the coast—where air, sea, land, and people meet

We are all stewards of the coastal ocean. For some of us, the connection to the sea is clear and immediate; for others, it is subtle and distant. But whether you live on waterfront property or in a land-locked hamlet, your everyday activities affect this most sensitive and most threatened portion of the world's oceans.

Oil slicks in our harbors, sewage in our bays, and trash on our beaches provide obvious testimony to our links to the coast. So do the shrimp, salmon, and scallops on our dinner plates, and the money in the wallets of the millions of business owners and employees who make their living on the water's edge. Hundreds of thousands of buildings stand within reach of a storm surge from the ocean.

The subtle connections to the sea reach hundreds of miles inland. Air pollution from cars, trucks, and factories eventually precipitates into the ocean. Pesticides sprayed on lawns and golf courses run off into rivers, get ingested by fish downstream, and eventually poison shorebirds that never fly near those lawns or golf courses.

Few farmers in Midwestern states think of how their activities affect the ocean, but they should. Ever since Fritz Haber discovered in 1908 how to remove nitrogen gas from the atmosphere and turn it into fertilizer, the amount of nutrients applied to farmlands has increased dramatically. Perhaps two-fifths of the world's population would not exist were it not for this affordable and inexhaustible supply.

The downside is that much of this nitrogen runs off the farms and finds its way into the coastal ocean. Nitrogen and other nutrients stimulate the growth of microscopic marine plants, which in turn feed marine animals. But sometimes the fertilizer promotes too much plant growth, crowding out many species and suffocating others. The headline from a recent series in *The Baltimore Sun* says it all: "Nitrogen's deadly harvest: feeding the world, but poisoning the oceans."

The coastal ocean is a precious, narrow strip of water extending from the edge of the continental shelf to the estuaries where salt water and fresh water meet. It is the most biologically productive part of the ocean, and this wealth of activity influences, and gets influenced by, the cycles of carbon and other elements that govern climate and human life itself.

The growth of the human population—and the means used to achieve that growth—increasingly threaten nearshore waters. We have heard the statistics. Half of Earth's population lives within 50 miles of a coast. Coastal areas supply 90 percent of the world's fish catch and 25 percent of U.S. oil. More than 80 percent of U.S. global trade passes by ship through our harbors. Beaches and coastal waterways are fertile territory for tourism and recreation, the largest sector of the U.S. service industry.

Other statistics are less known but more worrisome:

- Eleven of the world's 15 most productive fishing grounds—and 70 percent of the major fish species in them—have been or will soon be overexploited.
- Within 60 years, one of every four

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Chatham, Mass., photo by Steve Heaslip, *Cape Cod Times*

houses within 500 feet of the shoreline could be destroyed due to sea-level rise and inappropriate coastal development.

• The bottom of all the oceans' continental shelves are trawled by fishermen at least once every two years, with some areas scarred by nets and chains several times a season.

• At any given time, several thousand species are being carried from one location to another in ship ballast tanks, ready to invade and colonize distant habitats. In San Francisco Bay alone, 234 invasive species have become established, and a new species successfully invades every 14 weeks.

The news is not all bad. Coastal waters in some regions are cleaner than they've been for decades, thanks to efforts to reduce chemical and nutrient pollution. Marine aquaculture operations are reducing the pressure on wild-capture fisheries. Some states are creating no-build zones in sensitive coastal areas, preventing development that is incompatible with the dynamic nature of the shoreline.

Pat Tester, NOAA

Donald Anderson, Director of the WHOI Coastal Ocean Institute and Rinehart Coastal Research Center.

This issue of *Oceanus* provides background on many of these problems and promising developments. The articles that follow highlight the role that science must play in society's approach to everything from oil pollution and algal blooms to wind power and shifting shorelines.

New technologies, new approaches to coastal research, and new collaborations among scientists from different disciplines are setting the stage for scientifically based management of the coastal zone. Resource managers and elected leaders are desperate for ideas and guidance about how to manage our relationship with the ocean. Many of the answers they need require new scientific inquiry, as well as better explanation of what we already know.

This is the mandate of the Coastal Ocean Institute (COI). Through research grants, scientific gatherings, and the development of state-of-the-art facilities, the Institute encourages innovative, interdisciplinary research and technology development that can improve our understanding of the processes at work along our shores. COI also fosters communication efforts to help civic leaders, students, and citizens become better informed about the complexities of this dynamic environment and the possibilities for sustaining and restoring it.

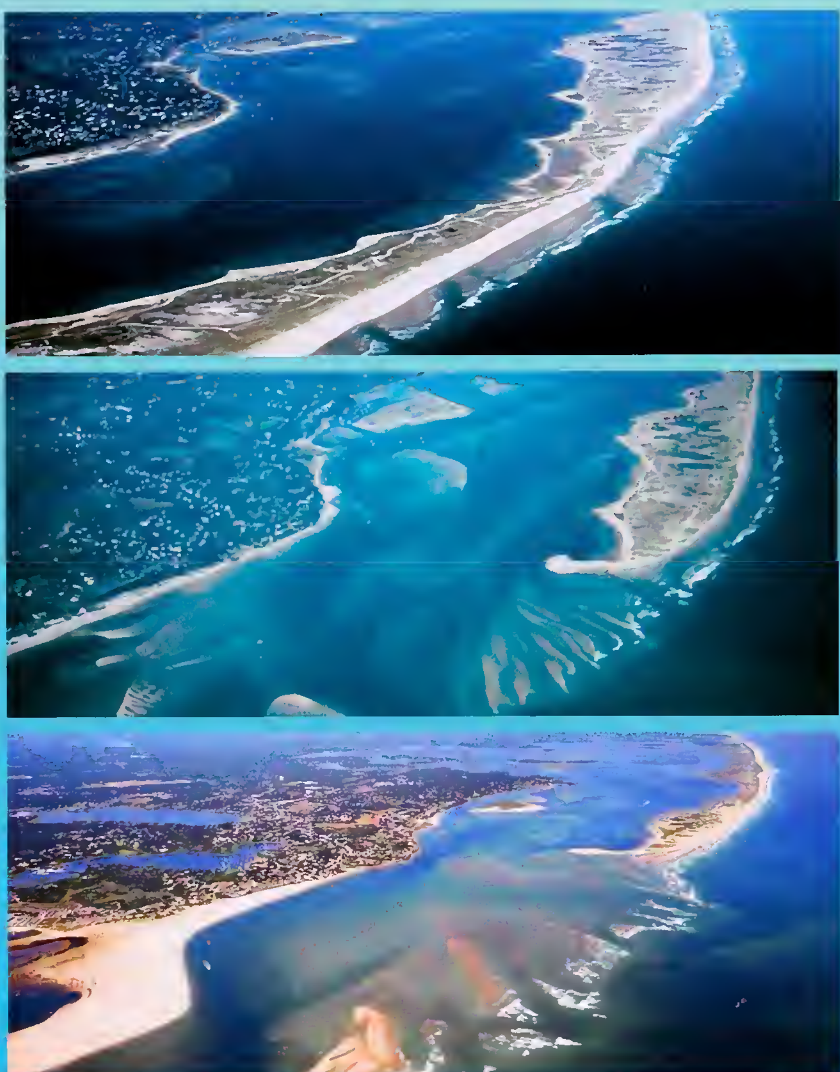
Coastal waters are the ocean's first line of defense, and that line is showing many signs of stress. The first step in promoting effective stewardship is to recognize and document the problems; as you will read, we are far along in that regard. The challenge now is to move our scientific understanding forward to a point where we can reduce or eliminate some of these problems.

—Donald M. Anderson

Rising Sea Levels and Moving Shorelines

New tools and techniques show promise for better predictions and decisions about coastline change

Breaching the beach



Top photos courtesy of Duncan Fitzgerald, Boston University; bottom photo by Joseph R. Melanson, skypic.com

The shoreline of Chatham, Mass., has been battered and reshaped by potent Atlantic winds and waves for centuries. This series of photos shows the barrier beach in 1985, 1986, and 1995, before and after a winter nor'easter created a new inlet. Improved understanding of how shorelines change over time can help coastal managers to better plan development and respond to recurrent or episodic threats.

By Rob L. Evans, Associate Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Nae man can tether time or tide.
—Robert Burns

For the past century, the pace and density of development near the ocean has been unprecedented, and much of it is incompatible with the dynamic nature of the shoreline. More than $3 trillion are invested in dwellings, resorts, infrastructure, and other real estate along the Atlantic and Gulf coasts of the United States, and more than 155 million people live in coastal counties. The coastal population is estimated to rise by 3,500 people per day.

Yet, as the devastating hurricane season of 2004 showed, there is a price to be paid for living at sea level and building on sand. Even without extreme storms, the shoreline naturally advances and retreats on scales ranging from seconds to millennia.

As a growing population hugs the coast, understanding the complex processes by which coastlines change has never been more relevant and more important to our well-being.

A rising tide

Changes to the shoreline are inevitable and inescapable. Shoals and sandbars become islands and then sandbars again. Ice sheets grow and shrink, causing sea level to fall and rise as water moves from the oceans to the ice caps and back to the oceans. Barrier islands rise from the seafloor, are chopped by inlets, and retreat toward the mainland. Even the calmest of seas are constantly moving water, sand,

and mud toward and away from the shore, and establishing new shorelines.

Coastal changes have accelerated in the past century. Although sea level has been rising since the end of the last glaciation (nearly 11,000 years), the rate of sea-level rise has increased over the past 200 years as average temperatures have increased. Global warming has added water to the oceans by melting ice in the polar regions. But the greater contributor is thought to be thermal expansion of the oceans—a rise in sea level due to rising water temperature. Sea level has risen 10 to 25 centimeters in the past 100 years, and it is predicted to rise another 50 centimeters over the next century (with some estimates as high as 90 centimeters). Whether or not human activities have contributed to the change, the sea is definitely rising, and it jeopardizes our rapidly growing coastal communities.

Coastal erosion accelerates as sea level rises. Erosion decreases the value of coastal properties because it decreases "the expected number of years away from the shoreline," as researchers and underwriters put it. This quiet loss of U.S. property value amounts to $3 to $5 billion per year. Then there is the actual loss of property, including structures, which amounts to as much as $500 million a year.

Eroding coastlines are also at greater risk from storm damage. Property damage from hurricanes along the eastern U.S. is estimated to average $5 billion per year, with the cost in 2004 alone estimated at more than $21 billion. Such calculations rarely account for the long-term costs of flooding and erosion, damage to natural landforms or ecosystems, and lost recreation and tourism opportunities.

There is significant debate about how to best manage coastal resources to cope with the changing shoreline. When and where will the coast change? And what, if anything, should we do about it?

Billions of tax dollars are being spent to restore and protect our wetlands, maintain our beaches and waterways, and rebuild coastal infrastructure. For example, the State of Louisiana is proposing to spend $14 billion over the next 40 years to restore coastal barriers along the Mississippi River delta. Despite these vast sums of money, very little is being invested in basic research that can improve our ability to predict shoreline change, inform coastal managers in their decision-making, or provide more accurate risk assessment.

More than just a beach problem

The coast is an incredibly complex system, of which beaches are only one part. All aspects of the system—rivers, estuaries, dunes, marshes, beaches, headlands, the surf zone, and the seafloor—influence and respond to the others. But many parts of the system have yet to be studied in sufficient detail to fully understand their roles in shoreline change.

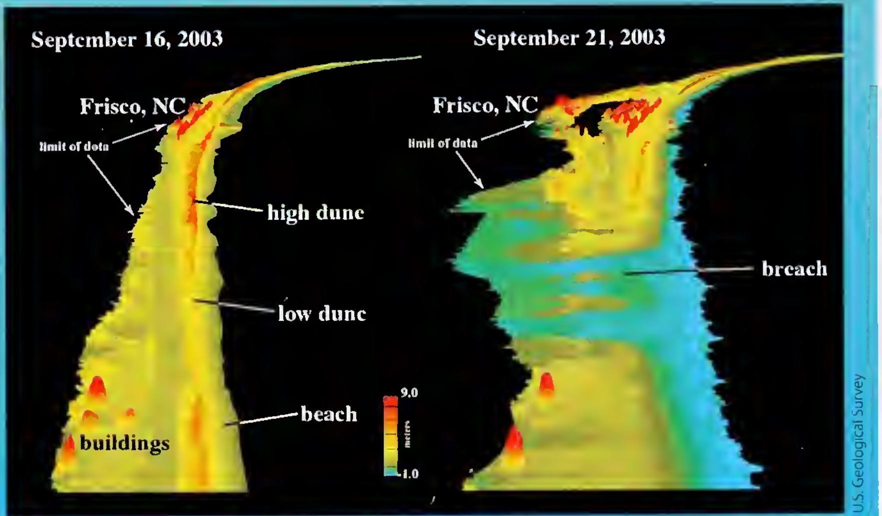
Beach erosion threatens property near the shoreline, but it also profoundly influences a critical part of our coastal ecosystem: the marshes. Tidal marshes in estuaries and behind barrier islands are the dominant habitat along the Atlantic Coast of the U.S., and they are particularly vulnerable to rising sea level.

Marshes are ecologically and economically important because they regulate the

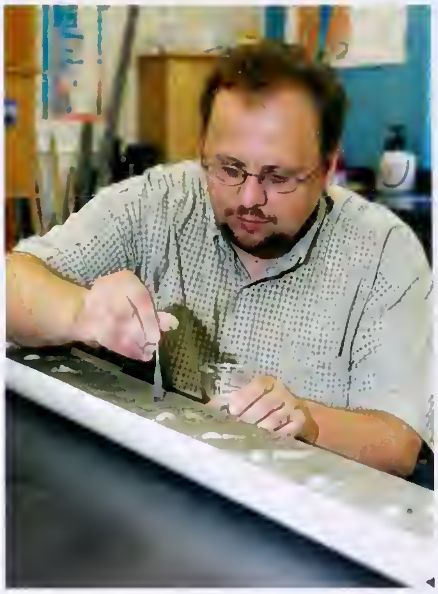
A rising tide along the coast

Never before has coastal research been more relevant and more important to society's well-being. The numbers are staggering:

- More than 155 million people (53 percent of the population) live in U.S. coastal counties which comprise less than 11 percent of the land area of the lower 48 states.
- Roughly 1,500 homes are lost to erosion each year.
- Nearly 180 million people visit the U.S. coast every year, and coastal states account for 85 percent of U.S. tourism revenues. The tourism industry is the nation's largest employer and second largest contributor to gross domestic product.
- 71 percent of annual U.S. disaster losses are the result of coastal storms.
- Close to 350,000 homes and buildings are located within 150 meters of the ocean. Within 60 years, one out of every four of those structures will be destroyed.



Light detection and ranging (LIDAR) images gathered by airplane reveal extensive beach changes and dune erosion on Hatteras Island, N.C., which was breached by the storm surge from Hurricane Isabel in September 2003. The images show elevation above sea level, with reds signifying the highest elevations and blues representing the water line. The breach occurred where the island was narrowest and the dune heights were lowest.



Photos by Tom Kleindinst, WHOI Graphic Services

DIGGING FOR EVIDENCE—Scientists from the WHOI Department of Geology and Geophysics are applying numerous techniques to understand how the shoreline is changing in response to rising sea level. Left: Assistant Scientist Liviu Giosan (tan shirt) and Graduate Student Jonathan Woodruff extract sediments from the beach using a vibracorer. Middle: Assistant Scientist Jeff Donnelly holds a core of mud and sediment pulled up from a marsh. Right: Giosan prepares sediments from a split core for laboratory study.

exchange of water, nutrients, and waste between dry land and the open ocean. They filter and absorb nutrients and pollutants, and buffer coastlines from wave stress and erosion. And tidal marshes provide nursery grounds for countless species of fish and invertebrates. They are among the most biologically productive ecosystems in the world, producing more biomass per area than most other ecosystems.

Whereas researchers have been studying the fertility and biologic productivity of marshes for many years, they have only recently started to determine how these coastal wetlands grow and erode. As sea level rises, we need to know the threshold at which marshes can no longer grow fast enough to keep pace with rising waters. If the rate of sea-level rise doubles over the next 100 years—or quadruples, as some more extreme models project—tidal marshes and coastal ecosystems will likely experience unprecedented changes. Some may disappear altogether. Our coast may return to its condition at the end of the last glaciation, 11,000 years ago, when sea level was rising too fast for marshes to be established.

New toys for the sandbox

Although there has been progress in many areas of coastal geology, our understanding of the fundamentals of shoreline change has been limited by the lack of a broad and integrated scientific focus and a lack of resources. In many locations, we cannot answer simple questions, such as where sand goes after it is eroded from the beaches, or what role underwater formations play in determining which areas of the coast will erode and accrete.

Recent advances in technology make this an ideal time to tackle some of these science problems. Our ability to map, measure, model, and understand the fundamental processes shaping the shoreline has never been better. We can gather a more precise record of long-term trends in shoreline motion, which were previously identifiable only through historical records, such as by comparing old nautical charts with modern ones.

Several instruments have allowed us to make dramatic improvements in our ability to map the beach and seafloor, and what lies beneath.

- Light detection and ranging (LIDAR) allows researchers to use radar-like pulses of light to map beaches and the bottom of clear, shallow waters. It provides maps that are precise to within 10 centimeters.
- Global Positioning System receivers and monuments use satellites to track the movement of shoreline features from day to day in three dimensions. These devices allow positions to be obtained accurately to within a few centimeters.
- High-resolution seismic imaging, ground-penetrating radar, and electromagnetic resistivity instruments employ sound and electrical signals and the properties of rocks and sediments to "see" the layers beneath the beach surface and seafloor. They can probe to depths of tens of meters.

The processes that shape our coasts occur on a variety of time and space scales. Linking these diverse processes is a challenge that requires a system-wide, multidisciplinary approach. It also requires the willingness of policymakers and coastal managers to support basic research and to pay more attention to its results. There are several clear, process-based science problems that need to be addressed before we can accurately predict shoreline change.

How is the shoreline changing with time and geography?

Many studies of nearshore processes have been conducted on long, straight shorelines, and scientists have made some progress in understanding how waves, sandbars, and currents interact in simplified situations. But the mechanisms driving shoreline change are not well understood in regions where the nearshore region has complicated seafloor topography, inlets, or headlands—which means most beaches.

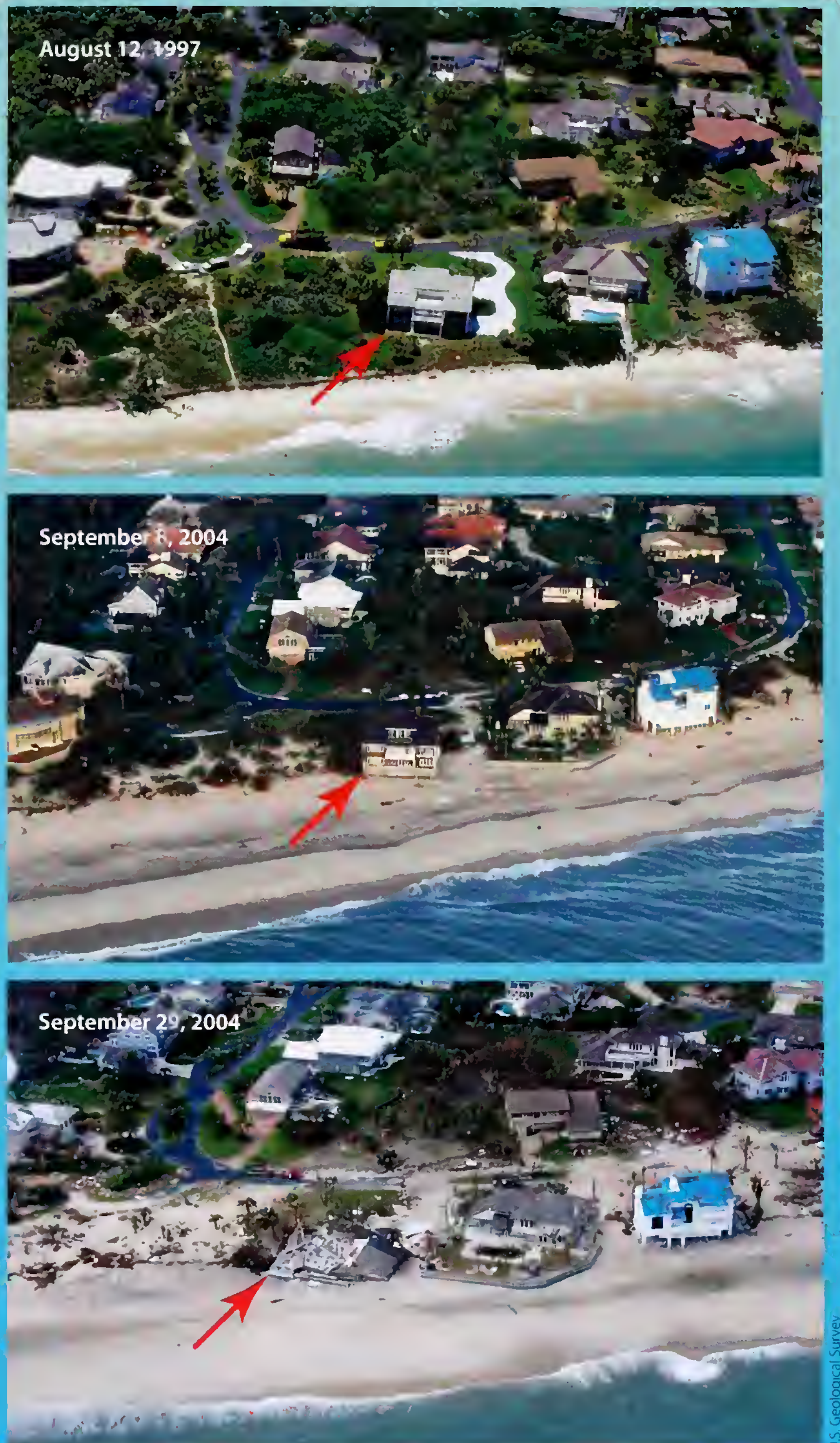
Waves traveling across the continental shelf are reflected, refracted, amplified, and scattered by underwater topography, and research has suggested that erosional hotspots along the coast are often the result of these seafloor formations. Banks, shoals, canyons, and even different types of sediment cause waves to decay and break differently. Wave-induced currents cause sediments to erode and accrete and reshape the seafloor near the coast, changing how future waves will evolve.

The complex dynamics between waves and seafloor evolution need to be unraveled before we can make predictions about changes to the shoreline. We need to build a network of wave-measuring instruments along different coastlines and feed those measurements into computer models of how the shoreline reacts to waves and currents. These models will help us make predictions about how water might circulate and how sediment might move in response to those different underwater formations. (See "Shaping the Beach, One Wave at a Time," page 12.)

How will barrier islands respond to sea level rise?

Barrier islands account for approximately 15 percent of the world's shoreline, and they dominate the Atlantic and Gulf coasts of the United States. Built by the action of waves and currents, these narrow ridges of sand usually run parallel to the mainland, protecting the coast from erosion. These natural barriers are bisected by tidal inlets and channels, and they shelter

Trouble in paradise



This sequence shows how the seas advanced and property was destroyed in Floralton Beach, Fla. Vegetation and dune lines were completely wiped away after Hurricane Frances (middle photo), leaving shoreline properties directly exposed to coastal surges from Hurricane Jeanne (bottom photo).

Tom Kleindinst, WHOI Graphic Services

ELECTRIC IDEAS—WHOI Associate Scientist Rob Evans (left) works with Engineering Assistant Matthew Gould to test a seafloor electromagnetic surveying instrument, one of many new technologies developed to better map and monitor the coastal system.

back-barrier salt marshes, tidal flats and deltas, and mangroves. Though usually no more than a few meters above sea level, these islands are often covered with human developments.

The long-term fate of today's barrier islands is dependent on future sea-level rise. The latest report of the Intergovernmental Panel on Climate Change predicts that global warming will cause sea level to rise by 50 to 90 centimeters in the next 100 years. At the higher end of these estimates, many back-barrier marshes will struggle to keep up with the inundation.

Sand will move from barrier beaches to the nearshore underwater regions in order to re-establish equilibrium between the slope of the beach and the higher tides and waves. The water levels and topography behind these barriers could gradually or catastrophically change. Inlets will become more dynamic, while deltas will enlarge. Whole marshlands might disappear, being converted to tidal lagoons or bays. Catastrophic amounts of sand could be lost from some beaches.

To properly protect barrier beaches—or learn when to abandon them—we need to map and monitor them regularly. We also need to dig into the sediments of the coast to piece together the history of past changes. Such efforts will allow us to model how tidal systems are likely to respond to rising ocean waters.

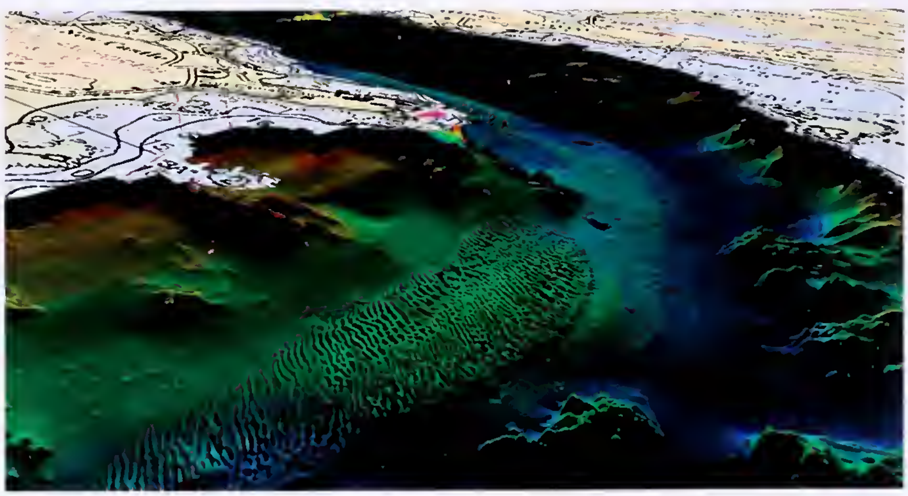
What is the impact of storms?

Intense storms such as hurricanes, nor'easters, and typhoons often result in substantial loss of life and resources, yet we know little about the processes that govern their formation, intensity, and movement. Nor do we know much about their history, due to the relatively short history of reliable weather observations. With little data on how coastal systems have responded to storms in the past, we have been ill-equipped to model and project how climate and sea-level change will affect future storm trends.

Geological investigations of coastal environments can provide long-term records of environmental change. Evidence of past storms can be found in back-barrier sediments: When a storm washes sand over the dunes and into back bays and marshes, it forms dateable layers in the muddy sediments. Mapping regional occurrences of these "overwash" deposits can allow researchers to estimate the storminess of years past and help improve models of the probability of future storm strikes.

How is the shore linked to the shelf?

In the past, studies of the beach and surf zone were usually separated and studied independently from what was happen-



Larry Mayer, University of New Hampshire

MAPPING THE SEAFLOOR BY LASER—Researchers used LIDAR instruments to generate this seafloor map of the Piscataqua River inlet between Kittery Point and New Castle Island on the border between New Hampshire and Maine. New imaging techniques are allowing coastal scientists to visualize the geologic framework of the coastline, track major movements of sediment, and project how the shoreline might change with time.

ing farther out on the continental shelf. It has largely been a logistical problem, as the region from 0 to 10 meters of water depth can present some of the most difficult areas to sample. These areas are too shallow for most ships, and too deep or turbulent for researchers on foot. However, the zone from 10 meters above sea level to 10 meters below is perhaps the most physically dynamic and ecologically vulnerable. If we are to fully understand the coastal system, we have to eliminate the imaginary barrier between the shallows and the deep.

What can the past tell us about the future of the shoreline?

Natural records from a variety of sources—deep-sea sediments, ice sheets, corals, calcium carbonate formations in caves—show that abrupt environmental changes are common in Earth's history. Sea level rise rates during the past 11,000 years have been uncharacteristically steady, and may be ripe for change. That our coastlines have developed such remarkable diversity during these stable times (environmental stress usually promotes diversity; calm promotes homogeneity) suggests the shape of the shore is affected by a lot more than sea level.

Coasts are complex, transitional environments that respond to changes in both continental and deep-ocean processes. The sediments onshore and offshore are great recorders of this variability, yet these archives have yet to be systematically studied and compared with what we have learned from inland and deep-sea environmental proxies for climate.

Tom Kleindinst, WHOI Graphic Services

BURIED CLUES—WHOI Assistant Scientist Ilya Buynevich demonstrates a ground-penetrating radar instrument on a beach in Cotuit, Mass. By bouncing radar waves off buried rocks and sediments, he can create maps of subterranean layers and extrapolate past sea level.

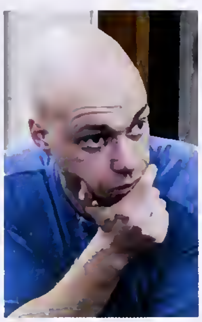
The high stakes of high water

Resource managers and civic leaders have a great responsibility for managing the coast and human use of it, but they have not always had the best information available to make scientifically sound decisions. The link between sea-level rise and shoreline change, while undoubtedly present, remains controversial.

For this reason, coastal managers want more reliable data on sea-level rise. They need studies that apply our knowledge of basic processes to more complex, human-altered shorelines (seawalls, bulkheads, jetties, groins). They need scientific analyses of the effects of adding and removing sediments from the shoreline.

There is no doubt that sea level is rising. It's not the first time, and the rate at which it is changing may or may not be unusual. What is different this time is that humans have congregated along the shoreline without much awareness of how much or how soon the sands might shift. We have the ability to make better decisions about our lives along the coast. We just have to start making the measurements that can provide the right answers.

—This article is the result of a workshop held at WHOI in April 2004. Many colleagues who attended that meeting—too numerous to list—contributed to this article. I'd like to thank them.



Tom Kleindinst, WHOI Graphic Services

Rob Evans was an undergraduate in the Physics Department at the University of Bristol in England when he saw an advertisement for a Ph.D. project that involved a cruise to a mid-ocean ridge known as the East Pacific Rise. Undeterred by the fact that he knew next to nothing about mid-ocean ridges, he applied for the studentship at Cambridge University and the cruise to a sunny location. Since then, Evans has collaborated with most of the research groups in the world that carry out electromagnetic studies of the seafloor. He was a postdoctoral scholar in Toronto, before coming to the Woods Hole Oceanographic Institution as an Assistant Scientist in 1994. More recently he has started working closer to shore. His lack of hair is a result of the stress of doing marine science and has no relationship to his heavy use of electromagnetic fields.

Shaping the Beach, One Wave at a Time

New research is deciphering how currents, waves, and sands change our shorelines

By Britt Raubenheimer, Associate Scientist
Applied Ocean Physics & Engineering Department
Woods Hole Oceanographic Institution

For years, scientists who study the shoreline have wondered at the apparent fickleness of storms, which can devastate one part of a coastline, yet leave an adjacent part untouched. One beach may wash away, with houses tumbling into the sea, while a nearby beach weathers a storm without a scratch. How can this be?

The answers lie in the physics of the nearshore region—the stretch of sand, rock, and water between the dry land behind the beach and the beginning of deep water far from shore. To comprehend and predict how shorelines will change from day to day and year to year, we have to:

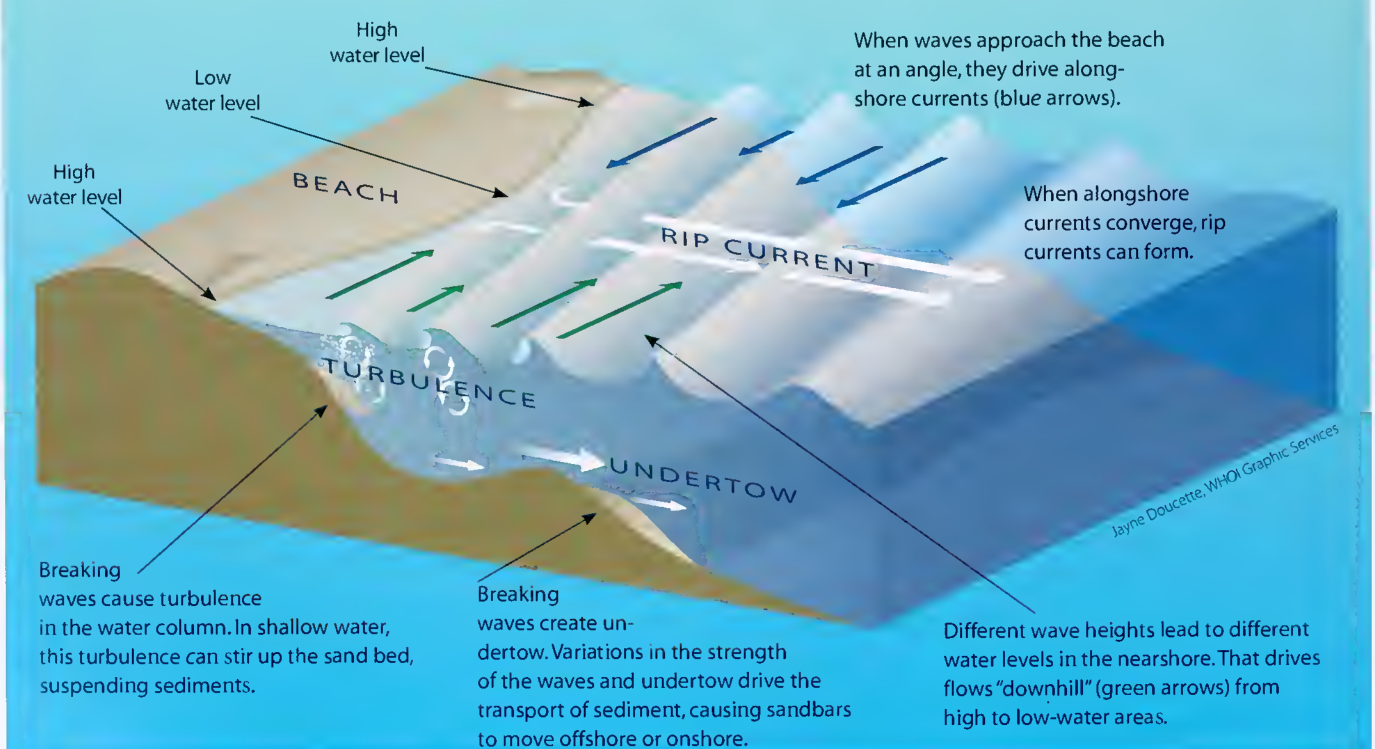
- decipher how waves evolve;
- determine where currents form and why;
- learn where sand comes from and where it goes;
- understand when conditions are right for a beach to erode or build up.

Understanding beaches and the adjacent nearshore ocean is critical because nearly half of the U.S. population lives within a day's drive of a coast. Shoreline recreation is also a significant part of the economy of many states. (See "Rising Sea Levels and Moving Shorelines," page 6.)

For more than a decade, I have been working with WHOI Senior Scientist Steve Elgar and colleagues across the country to decipher patterns and processes in this environment. Most of our

A mess of physics near the shore

Many forces intersect and interact in the surf and swash zones of the coastal ocean, pushing sand and water up, down, and along the coast. Variations in the height and direction of waves, as well as the shape of the seafloor, drive currents that rearrange the system.



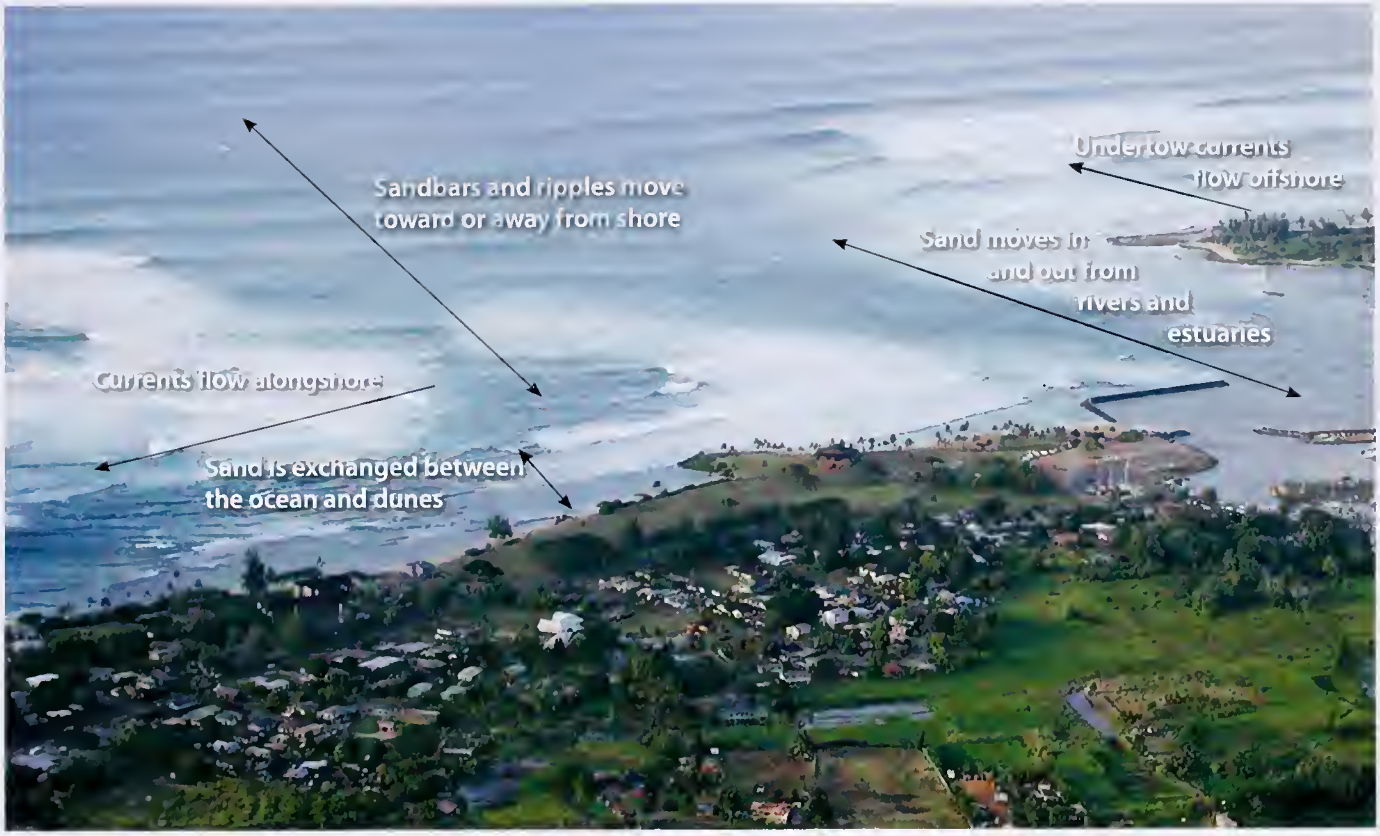
When waves approach the beach at an angle, they drive alongshore currents (blue arrows).

When alongshore currents converge, rip currents can form.

Breaking waves cause turbulence in the water column. In shallow water, this turbulence can stir up the sand bed, suspending sediments.

Breaking waves create undertow. Variations in the strength of the waves and undertow drive the transport of sediment, causing sandbars to move offshore or onshore.

Different wave heights lead to different water levels in the nearshore. That drives flows "downhill" (green arrows) from high to low-water areas.



Kimball McDonald, University of California San Diego

SWIRLING CURRENTS AND SEDIMENTS—Waves approach the beach from different directions in Haleiwa, Hawaii, driving alongshore currents of different strengths. As waves break, they generate turbulence that suspends sand and drives undertows.

work takes place in the breaking waves of the surf and swash zones: the region that begins where waves crest and ends where the foamy white water barely covers our feet.

Our goal is to understand and model waves, currents, and sand movement in the nearshore. Given weather conditions (winds, offshore waves), a map (islands, canyons, shoals, sandbars, the slope of the beach face), and sediment characteristics, we want to be able to model and predict how waves might change, and how those changes might affect currents and the erosion or accretion of sand on the beaches. To do this, we have to get into the water, making observations in the middle of the breaking surf.

If we are successful, we can help coastal policymakers and managers understand how the movement of water affects the evolution of coastlines, the safety of beachgoers, and the dispersal of runoff and pollutants.

What lies beneath

As storms and winds churn the ocean, waves roll across the continental shelf and into shallow water near the shore. They pitch forward and break, spraying foam and running up onto the beach. As the waves break, they drive currents that flow both offshore and along the coast.

Such is the view that most of us get when we stand on the shore. But what lies beneath the waves can make all the difference between 20-foot breakers and gently lapping rollers.

As waves move from deep water toward the shoreline, the ocean bottom alters their direction and strength, just as a lens bends and reflects rays of light. Features such as submarine ridges, canyons, and sandbars influence the propagation of waves, just as winds are directed and focused by mountains and valleys.

The breaking waves and resulting currents pick up and move sand, making beaches dynamic, perpetually in motion. This subtle but steadily flowing river of sand moves laterally up and down the shoreline, as well as offshore during storms and back toward land between storms.

Waves and currents affect this movement of sediment, but changes in sediment levels, in turn, affect the waves and currents. For example, sand eroded from the beach during winter storms may move offshore to form a sandbar. That causes waves to break farther offshore, protecting the beach from further erosion.

To avoid the complicated physics associated with along-coast changes in wave height and direction, most scientific studies of the nearshore have historically been conducted on smoothly sloping beaches with long, straight shorelines. The relatively simple shores of the Outer Banks of North Carolina have been a frequent focus for nearshore research. It was assumed that waves, currents, and sand levels were uniform up and down these beaches.

However, recent studies by Jeff List of

the U.S. Geological Survey have shown that even on these long, straight coastlines, one section of beach may recede shoreward by tens of yards during a storm, while a few miles down the coast the beach may be unaltered. Most of the eroded sand eventually returns after the storm, but that is no consolation to the owners of homes and structures destroyed by the shifting shoreline.

Stepping up to the bar

Several hypotheses explain the divergent erosion rates along the same coast. Perhaps there are differences in the underlying geology of the region or in the flow of groundwater to the ocean. Maybe something as subtle as the size of sand grains makes a difference. Or perhaps these seemingly "simple" and similar seafloors produce more changes in offshore waves than we think.

My research group is intrigued by a different theory: The location of underwater sandbars in the surf may cause variable erosion along the coast. Sandbars appear to protect beaches by causing increased breaking and dissipation of wave energy before the waves can attack the shoreline.

To test the sandbar hypothesis we used observations of waves and mean water levels collected at the U.S. Army Corps of Engineers' Field Research Facility in Duck, N.C. We found that sandbars affect coastal water levels and flooding during storms. When a sandbar is near the beach, waves break in shallow water and drive more water onto the shore. This causes flooding and allows the surf to reach dunes and manmade structures. We believe that shallow sandbars may lead to increased erosion.

Sandbar locations can be variable along straight coasts, which may explain Jeff List's findings. And recent aerial observations collected by Tom Lippmann of Ohio State University show that the numbers and locations of sandbars influence a storm's effect on a beach. But further research is needed to determine whether the feedback between sandbars and coastal water levels is important during storms.

Current events in the surf

In contrast to much of the East Coast of the United States, many continental shelves have abrupt, irregular changes in the seafloor that cause large changes in the waves beyond the surf zone.

For instance, the steep topography of Scripps and La Jolla submarine canyons in Southern California produces dramatic changes in wave energy over distances of a few hundred meters. As waves pass over the canyons, the seafloor acts like a magnifying glass, concentrating ocean wave energy into hot spots. This makes Black's Beach a world-famous surf spot, whereas La Jolla Shores (just two miles to the south) is well known to novice sea kayakers and scuba divers for its gentle waves.

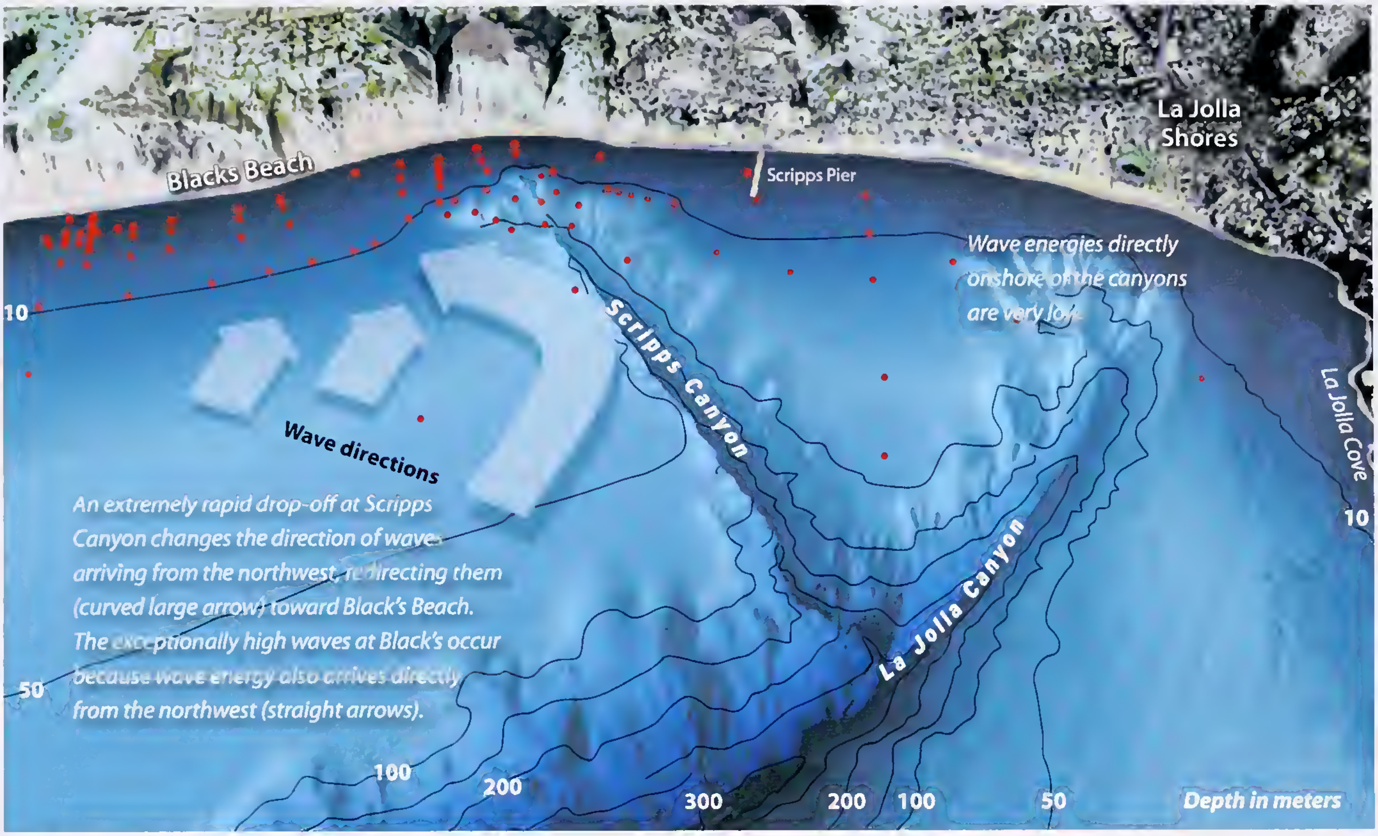
These changes in wave heights along the coast result in complex flows of water and changes to sand levels on the beach. Water that piles up on the shore near the large breaking waves at Black's Beach tends to flow south toward La Jolla Shores and north toward Del Mar. When these currents intersect with opposing currents—perhaps between the heads of the two canyons—strong offshore-directed flows, called rip currents, can form. Rip currents are a danger to swimmers and have been observed to carry huge plumes of sand and pollutants offshore.

Scientists from WHOI and 10 other institutions recently conducted a major field program in those complicated Southern California waters to determine how abrupt coastal seafloor topography affects waves, currents, and changes to sand levels. The team of more than three dozen scientists, engineers, students, and research assistants deployed instruments to measure the effect of the canyons on waves and the resulting changes in the flows onshore.

In the Nearshore Canyon Experiment (NCEX), sponsored by the Office of Naval Research and the National Science Foundation, my colleagues and I deployed pressure gauges and current meters in the surf and swash zones to measure wave heights and directions, and the resulting movement of water and sand. "Drifters" designed to operate in the breaking waves of the surf zone were used to determine the locations and speeds of rip currents. Beach

Herman C. Miller, U.S. Army Corps of Engineers

STORM SURGE—The ocean rushes onto the streets of South Nags Head, N.C., wiping out dunes and damaging houses during the "perfect storm" of 1991. Ocean waters wash over barrier islands during storms because winds push water against the shore, low atmospheric pressure allows water levels to bulge upward, and breaking waves force water toward the shore.



Paul Horn, Courtesy of *Explorations*, Scripps Institution of Oceanography

CHANNELING THE WAVES—The bottom topography of the Scripps and La Jolla submarine canyons directs and focuses wave energy near San Diego. Red dots show the placement of wave-measuring instruments from the Nearshore Canyon Experiment.

surveys were conducted frequently to see how the seafloor and sand levels evolved under changing surf conditions.

Other scientists bounced radar signals off the water surface to determine its speed, just as police use radar guns to track moving cars. Video cameras chronicled sea foam as it was carried along the coast by the complex currents.

We have only begun to analyze our observations, but eventually we will be able to update and improve numerical models of the important physical processes and test the model predictions with real-world measurements.

Beach forecasts

Our long-term goal is to predict coastal wave heights and directions, nearshore currents, and changes to beach sand levels. We may not achieve this goal until we can study nearshore processes on a wide range of coasts (for instance, rocky shorelines, peninsulas, and large bays), but it is achievable within our lifetime.

Surfers, sport-fishermen, and recreational boaters frequently use predictions of wave heights along the coast of Southern California, as generated by our colleagues from the Scripps Institution of Oceanography. The new NCEX measurements will improve the prediction models, helping not only those who play at the beach for the day, but also civic leaders who must manage our beaches and coasts for the long term.

One hundred years ago, we could not predict whether it would be sunny or rainy the day after tomorrow. Now we can predict the weather as much as 10 days in advance. By the middle of the 21st century, we ought to be able to predict the weather at the beach...both above and below the water line.

Tom Kleindinst, WHOI Graphic Services

Britt Raubenheimer decided to study physics during the ninth grade, when she had a choice between taking either physics or biology (which included cutting up cute little frogs). She fell in love with research while attending Middlebury College, as she worked with astronomers at an observatory in the Canary Islands to collect observations of a supernova remnant. Raubenheimer spent the vacations of her youth backpacking, handgliding, rock climbing, canoe camping, and backcountry skiing, so she knew she wanted to take her physics skills outdoors. She became interested in nearshore oceanography while studying coastal overwash during her first job, at the U.S. Geological Survey's office in Saint Petersburg, Fla. She completed her training with a doctorate in oceanography from the Scripps Institution of Oceanography. Now her job requires her to go to the beach and to scuba dive to deploy instruments. Raubenheimer recently received a Young Investigator Award from the Office of Naval Research and a Career Award from the National Science Foundation. As part of the latter award, she developed a program offering six-month undergraduate fellowships to expose students to scientific research.

The New Wave of Coastal Ocean Observing

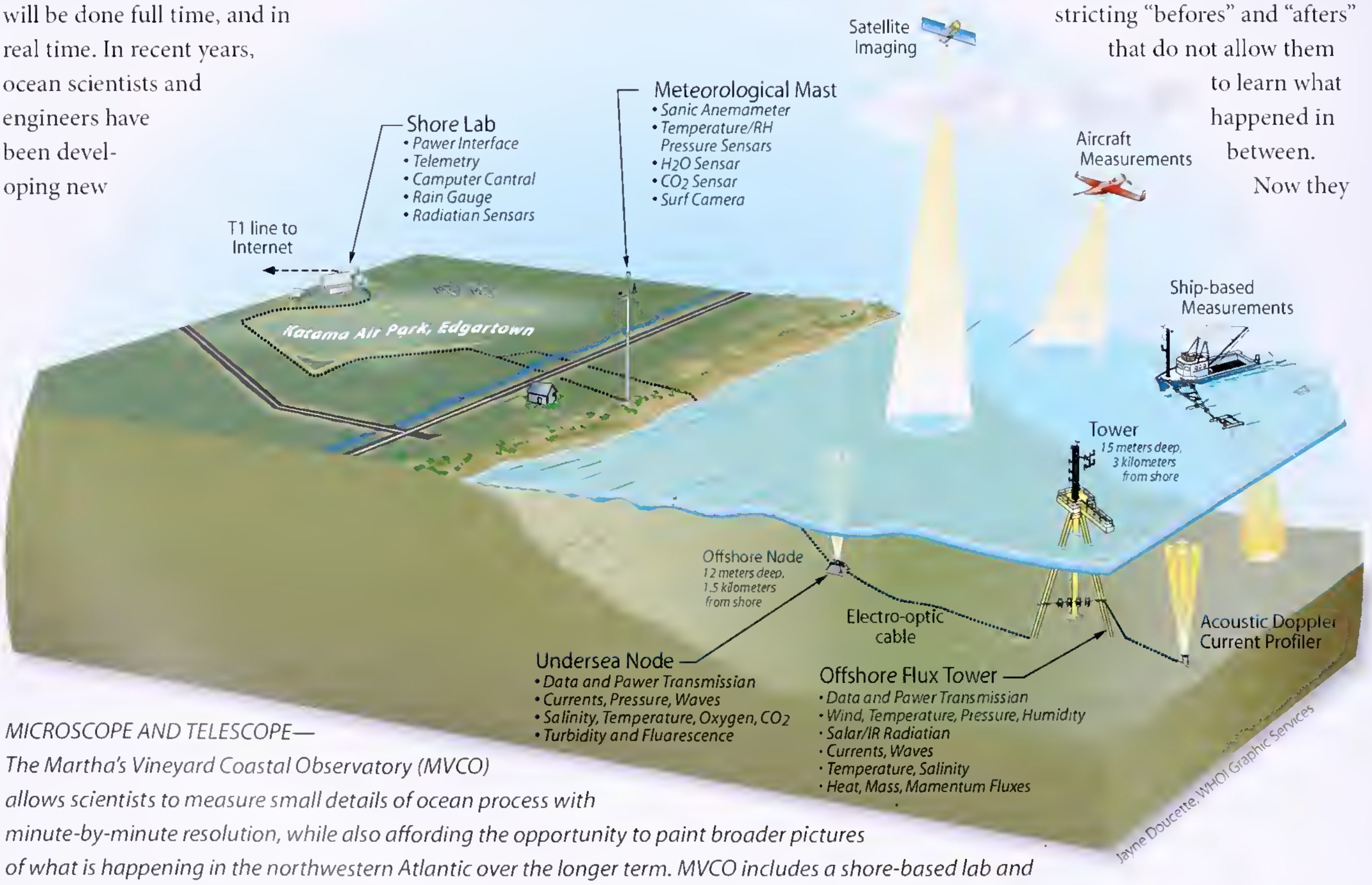
Shore stations and seafloor nodes provide connections for long-term studies of coastal processes

Most traditional means of observing the ocean have their limits. Research ships and submarines must return to port. Robots and moored instruments run out of battery power. Satellites have stamina but their view does not penetrate into the depths. Ships and subs can carry only a few scientists at a time, and never into dangerous but scientifically interesting conditions such as hurricanes. Consequently, scientists have had to be satisfied with intermittent glimpses of the environment.

The next wave of ocean science will be done full time, and in real time. In recent years, ocean scientists and engineers have been developing new ways to go to sea—and stay out there—without getting seasick. They have been plugging instruments into seafloor nodes connected directly to shore-based labs, and using electro-optic-power cables to transmit steady streams of power and data.

At locations such as the Martha's Vineyard Coastal Observatory (MVCO) operated by Woods Hole Oceanographic Institution, researchers have staked out a parcel of ocean and are observing it with 24/7 vigilance, with the potential to do so for years. They can continuously measure what is happening on the sandy ocean bottom, in the water column from the seafloor to the surface, and in the air above it. And they can do it while sitting at their desks. Thanks to the cables, data from the sea are freely available on the Internet in real time to an unlimited number of scientists.

Unconstrained by time, space, and foul weather, scientists are starting to use coastal observatories to move past the snapshots of ocean processes, the restricting "befores" and "afters" that do not allow them to learn what happened in between. Now they



MICROSCOPE AND TELESCOPE—The Martha's Vineyard Coastal Observatory (MVCO) allows scientists to measure small details of ocean process with minute-by-minute resolution, while also affording the opportunity to paint broader pictures of what is happening in the northwestern Atlantic over the longer term. MVCO includes a shore-based lab and meteorological mast, an underwater node, and a tower wired for instrumentation above and below the water line.

can illuminate processes. How do storms rearrange shorelines and seafloor sediments? What is exchanged at the interface between air and water, and how does it affect coastal weather? Why do currents change seasonally? How do environmental changes affect plankton at the base of the marine food chain?

New window on the Atlantic

Built in stages since 2000 on the south shore of Martha's Vineyard, MVCO provides a natural laboratory to study key coastal processes in the North Atlantic. Permanent and project-specific instruments have measured the motion and strength of currents, the movement of sediments, the cycles of microscopic plants and animals and the bottom-dwelling creatures that eat them, the exchange of gases and aerosols between the ocean and atmosphere, and coastal meteorology.

Just 90 minutes from Woods Hole on WHOI's coastal research vessel *Tioga*, MVCO is exposed to the open ocean and a wide range of conditions, including energetic tides and surface waves, and winds ranging from dead calm in summer to intense storms in fall and winter. In a seasonal rhythm, offshore waters become stratified in summer, with warmer surface waters atop denser, colder waters; in winter, the water column becomes homogeneous again.

The National Science Foundation (NSF) and Woods Hole Oceanographic Institution shared the costs to build a small, inland shore lab, a 10-meter mast with meteorological instruments at the ocean's edge, and a seafloor node 12 meters below the sea surface and 1.5 kilometers from the shore. Cables connect the sensors at the mast and sea node to computers and communications devices in the shore lab.

In 2002, the Office of Naval Research (ONR) provided support for the design, construction, and deployment of an Air-Sea Interaction Tower (ASIT) about 3 kilometers from Martha's Vineyard. The tower stands in 15 meters of water and extends 22 meters above the water line into the atmosphere. It is connected through its own fiber-optic cable to the shore lab.

The node and tower act as scaffolding and "extension cords," allowing scientists to install instruments in the coastal environment, then return home to collect data over the Internet. If equipment fails, they can quickly detect the problem and go fix it.

Jayne Doucette, WHOI Graphic Services

STANDING TALL—The Air-Sea Interaction Tower, built as part of an experiment sponsored by the Office of Naval Research, allows scientists to deploy instruments that monitor the relationship between winds and waves in all weather conditions.

Wind, rain, or dark of night

In addition to long-term, continuous, and easily accessible streams of data, coastal observatories provide other advantages. Structures such as MVCO can allow scientists to chronicle the processes at work during extreme events that were previously difficult to study.

For instance, scientists have spent decades making shipboard expeditions to measure how the air and sea exchange heat, water, gases, and momentum. But they have learned little about what happens when wind speeds exceed 40 to 50 knots because no ship captain will intentionally cruise into a hurricane and risk lives to make such measurements. Even in less extreme circumstances, the natural movement of a research vessel leaves scientists wondering how much of what they measure is real and how much of it is "ship noise."

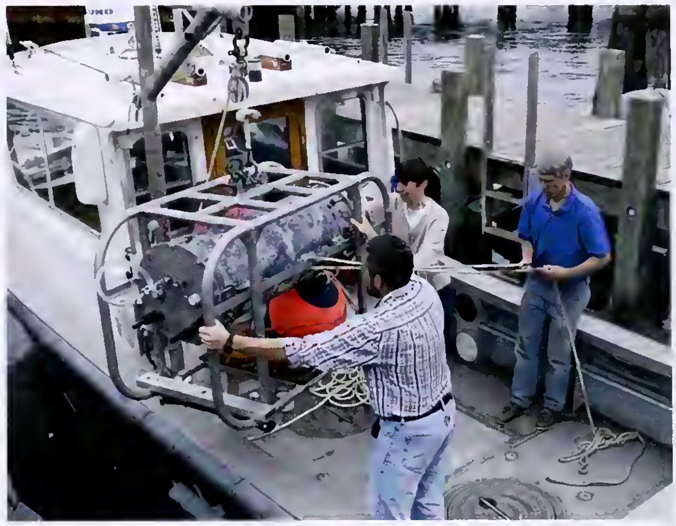
Coastal observatories also can help engineers who are developing and testing new instruments. For instance, researchers working on power-hungry, advanced sensors have plugged into MVCO to test the effectiveness of their instruments without the power limits of batteries or the time limits of ship-based expeditions.

Getting down to business

Today, WHOI scientists and engineers are working with colleagues from around the country, using MVCO for a variety of interdisciplinary and multi-institutional research projects. These have included:

- The Coupled Boundary Layers and Air-Sea Transfer (CBLAST) program, supported by ONR. This experiment, conducted in the summer of 2003, focused on the dynamic interaction between winds, waves, and ocean-mixing processes as they exchange heat, water, energy, and gases (such as carbon dioxide) between the ocean and atmosphere. These exchanges are fundamental processes that determine coastal weather and play a critical but oft-unappreciated role in global climate.
- Surface Processes and Acoustic Communications (SPACE), and Optics, Acoustics, and Stress In Situ (OASIS), supported by ONR. Investigators are evaluat-

Jayne Doucette, WHOI Graphic Service



Tom Kleindinst, WHOI Graphic Services

UNDERWATER POWER STRIP—Left: The seafloor node of the Martha's Vineyard Coastal Observatory, shown here being lowered into the water, supports experiments but it is also an experimental technology itself. Scientists plug into the node's power supply and data cables to study everything from shifting sands to blooming plankton. Right: New robotic technologies and cutting-edge instruments—such as the plankton-observing FlowCytobot—are tested at MVCO before heading off to projects in other regions.

ing how bubbles near the sea surface and suspended sediments in the water column affect the propagation of sound and light underwater. Bubbles, turbulence, and sediments accumulate and behave differently in shallow water—where the Navy is primarily working today—than in deep water—the region of most naval interest during the Cold War. The Navy relies on the accurate transmission and reception of sound and light signals for underwater communication and remote sensing.

• Plankton dynamics experiments, supported by NSF and the National Aeronautics and Space Administration. Long-term studies of plankton dynamics—to learn how, when, where, and why microscopic marine plants and animals flourish—take advantage of two newly developed instruments: the FlowCytobot and the Autonomous Vertically Profiling Plankton Observatory (AVPPO). FlowCytobot is a laser-based system to monitor and identify microscopic plankton down to individual cells. The AVPPO repeatedly records images of plankton scattered throughout the water column. Long-term deployment of such power-hungry instruments is only possible with the type of infrastructure at MVCO.

• Sediment transport experiments, supported by ONR. Researchers have been investigating the processes and factors—including winds, waves, currents, tides, and seafloor topography—that move sand and shape the seafloor around MVCO. In a related project, researchers have investigated the processes that bury objects such as military mines in seafloor sediments. (See "Where are Mines Hiding on the Seafloor?" page 62.)

• Ozone chemistry experiments, supported by NSF. Researchers have deployed instruments on the ASIT to quantify how much ozone pollution is being removed from the atmosphere and deposited into the ocean.

• Ocean Horizontal Array Turbulence Study (OHATS), supported by NSF. An air-sea interaction experiment is using 18 closely spaced sonic anemometers, or wind gauges, to examine the effect of ocean waves on air turbulence and eddies. The observations, begun in August 2004, should allow researchers to improve weather prediction models.

Building for today and tomorrow

With initial experiments underway and some lessons already learned at MVCO, WHOI scientists and engineers are making plans to improve and expand the facility.

Autonomous underwater vehicles (AUVs) and other robotic vehicles will likely play an important role in future studies at MVCO and other ocean observatories. Researchers can use observatories as remote ports from which they can launch these vehicles into inaccessible regions and extreme conditions. Equipment is already being tested to allow AUVs to download data and recharge their batteries at underwater nodes.

WHOI researchers are also working with colleagues at other institutions to create a network of coastal observing systems extending from the Gulf of Maine to Florida. By linking observations of several observatories along the East Coast, researchers will be able to develop a clearer picture of the long-term cycles and processes at work in the northwestern Atlantic. From hurricanes to migrating marine life to eddies spinning off from the Gulf Stream, coastal observers will be able to track developments in the ocean from start to finish and season to season. The result will be a more precise view of everyday life in one of the world's oceans.

—Written by Mike Carlowicz, WHOI Science Writer, with WHOI Senior Scientist John Trowbridge and Associate Scientists James Edson and Heidi Sosik.

The Grass is Greener in the Coastal Ocean

Coastal waters teem with life, but sometimes scientists can't explain why

By Kenneth H. Brink, Senior Scientist
Physical Oceanography Department
Former Director, Coastal Ocean Institute
Woods Hole Oceanographic Institution

Stretching from inland rivers and bays to the edge of the continental shelf, the coastal ocean accounts for about 10 percent of the ocean's surface area. Yet this relatively small sliver of ocean contains about half of all the microscopic plants adrift in our seas.

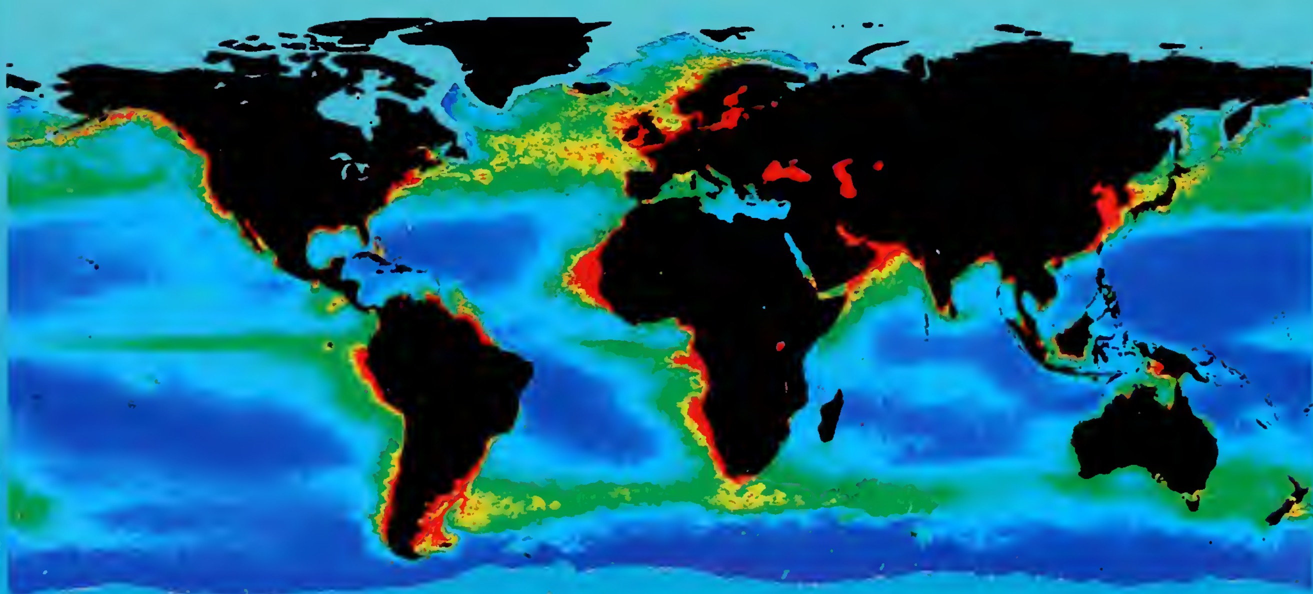
With satellites we can see what fishermen find with their nets: coastal waters are the most biologically productive portions of the world's oceans. Acre for acre, the coastal ocean is as productive as a prosperous Midwestern farm.

This is not necessarily a surprise. Microscopic plants, or phytoplankton, form the base of most of the food webs in the ocean. Microscopic animals (zooplankton) eat the phytoplankton, and are in turn eaten by other, larger animals. Increased biological activity by plants enhances animal activity.

Most of the world's great fisheries lie within coastal waters. But why is this area so much more productive than the rest of the ocean? Growing microscopic plants is like growing a lawn: both nutrients and light have to be available in the right quantities to allow photosynthesis to take place. Since light typically penetrates just the top 50 to 100 meters (150 to 300 feet) of the ocean, the problem comes down to having a sustained supply of nutrients in the upper layers of the water.

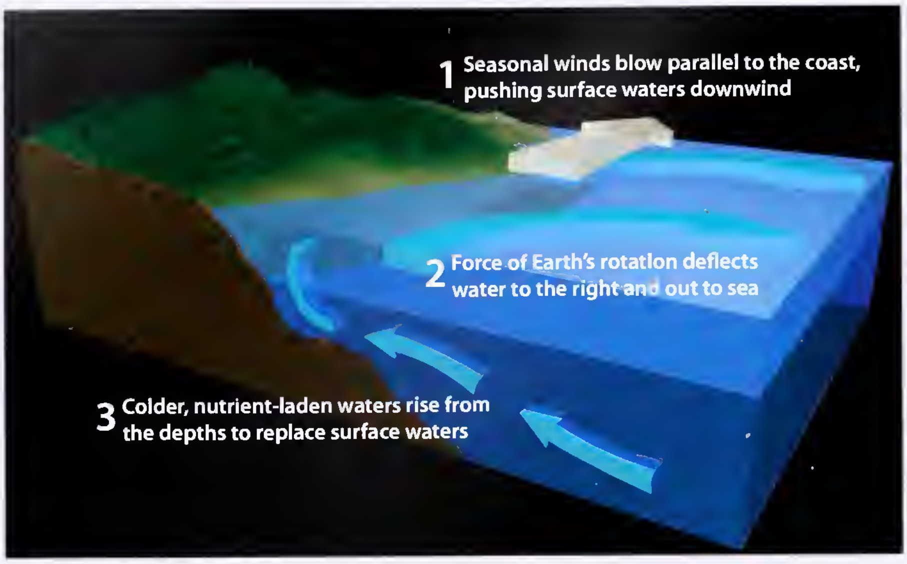
In the deep, open ocean, when nutrients become available near the surface, plants bloom, die, decay, and sink, often to a depth where there is no light. Instead of being recycled, the nutrients consumed by these plants accumulate in the depths, out of the reach of new plants. So while the open ocean can experience transient

Hot spots along the coast



Using satellite data, scientists can estimate how quickly microscopic plants are growing in the ocean. Red and yellow colors indicate regions of fastest growth, revealing the fertility of coastal waters. Tiny plants known as phytoplankton form the base of the food web, providing food for microscopic animals that in turn provide food for larger animals.

Courtesy Institute of Marine and Coastal Sciences, Rutgers University



NUTRIENTS FROM THE DEEP—Strong winds blowing along the coast can promote a phenomenon known as upwelling. The waters off California, Peru, and western Africa—where upwelling provides abundant nutrients—include some of the world's most productive fisheries.

blooms, there is usually not a sustained supply of nutrients in the upper ocean to promote plant activity.

Mighty winds and lazy rivers

The coastal ocean teems with life because there are mechanisms for tapping this store of deep nutrients and for drawing plant food from other marine environments. There is no one mechanism at work on every coast, but different processes at work in different places. Some are well understood, while others remain a mystery.

One well-understood example is wind-driven coastal upwelling, a process that taps into the store of nutrients stockpiled in the deep. Along some coastlines, strong winds blow parallel to the coast during certain seasons. These persistent breezes push water downwind, while the force of Earth's rotation (called the Coriolis force) deflects water to the right of the winds (left in the southern hemisphere). As a result, the waters in the turbulent upper 10 to 30 meters of the ocean are blown offshore, drawing colder, nutrient-laden waters from the depths to replace them.

The surface waters in regions of coastal upwelling are cold and nutrient-rich, promoting robust growth of plants and the animals that feed on them. But this mechanism can only be effective in places where the winds blow in the right direction.

These special places—coastal California, the Iberian-Canary system off Spain and Portugal, coastal Peru and Chile, and the Benguela system off southwestern Africa—are home to some of the world's most important fisheries. As much as 40 to 50 percent of the world's commercial fish catch comes from upwelling areas that comprise just 1 percent of the global ocean.

Another well-known mechanism for coastal productivity is river outflow. Natural and manmade nutrients—principally nitrates and phosphates—run off the land and fertilize marine plants. River outflow is best known for building productive regions in the North Sea and in the Gulf of Mexico. (See "Where the Rivers Meet the Sea," page 22.)

This fertilizer can be a mixed blessing. When too many nutrients are released into seas, bays, and estuaries, they can create an overabundance of decaying plants and animals, depleting oxygen from the water. These nutrient-rich, oxygen-poor waters become dead zones, driving animals to migrate or die. This may be the greatest threat to the health of our marine environment. (See "Red Tides and Dead Zones," page 43.)

Unsolved mysteries

While the fuel for some productive coastal zones is well understood, it is sur-

THE BIG MUDDY—A satellite image shows the flood of sediment pouring out of the Mississippi River into the Gulf of Mexico (more than 500 million tons per year). The torrent of nutrients feeds blooms of marine plants, creating one of the ocean's most biologically productive regions. But an overabundance can cause microscopic plants to grow, die, and decay so fast that they create "dead zones" (blackened waters) that can linger for months.

prising how little we understand about other historically important regions.

Georges Bank off the New England coast is one of the world's most productive fisheries and known to sustain high production of microscopic marine plants. Wind-driven upwelling cannot be a factor here and the region is too far from land for runoff to be important.

The Georges Bank system is dominated by extremely strong tides and sharp fronts, where water masses with stark differences in temperature or salt content intersect. There are several similar systems around the world—including the Yellow Sea and the Grand Banks—but no one has directly observed a means for providing nutrients in these areas. In the past few years, researchers have proposed some sound hypotheses and theoretical models involving the interplay of tidal pumping and ocean mixing. But none of those theories has been tested in nature.

While there is no solution to the Georges Bank enigma, at least there are some promising hypotheses. In the Gulf of Alaska, we don't have a clue. None of the well-understood mechanisms work in this incredibly productive region. The winds blow in the wrong direction and the coastal runoff is pure, low-nutrient water. There is no strong hypothesis to account for the productivity of the area, though that does not stop the fishing boats from proving the waters are rich.

A FINE KETTLE OF FISH—Most of the world's great fisheries lie in coastal waters. Scientists can explain why many areas are teeming with life, but other productive regions defy explanation.

Fishing for answers

How could we still have such gaps in our fundamental knowledge as we begin the 21st century? Perhaps the biggest reason is the cost and difficulty of making observations in the ocean. We just don't have good factual descriptions and observations of some regions, although coverage is rapidly improving around the United States.

It is only through direct observations that we can detect nutrient pathways or at least gather enough clues to allow the formulation of strong hypotheses based on computer models. Our biggest challenge is to develop and improve our ability to make these observations—of nutrients, currents, and the abundance of phytoplankton—in the right places, at the right times, and at rates and scales that can be compared. This means collecting data over months and years, rather than through isolated, intermittent expeditions.

We are at a wonderful juncture where critical new ocean technologies are in sight, and we have the right sort of questions and problems to solve with them. Some tools are emerging—particularly autonomous underwater vehicles, remote sensors, and coastal observatories—that promise to make our observations more specific and more quantitative. At the same time, our numerical models are becoming increasingly realistic and useful. This interplay of models and observations is proving extremely productive, as in the case of Georges Bank, where we now have a specific hypothesis to test.

The reasons for understanding productivity in the coastal ocean extend well beyond the curiosities of pure science and the livelihood of fishermen. The biological activity along our coasts has important implications for human activity on the land.

For instance, toxic blooms caused by polluted and excessively fertilized waters can hamper recreation and sicken humans and marine life. Also, as marine creatures generate wastes, decompose, and sink, they provide a means for removing carbon from the upper layers of the ocean and, in turn, removing greenhouse gases from the atmosphere.

The coastal environment is the most familiar and most connected with human life. It is also most affected by human activity. Understanding the reasons for the marvelous abundance of life in these regions will give us a means to ensure our own life along the water's edge.

Tom Kleindinst, WHOI

Ken Brink was educated at Cornell and Yale Universities, and has conducted research at WHOI since 1971. From 1996-2001, he served as chair of the Ocean Studies Board of the National Research Council. Brink also has served as president of The Oceanography Society and as a member of the Science Advisory Panel of the U.S. Commission on Ocean Policy. From 2001 to 2004, he was director of the WHOI Coastal Ocean Institute. He is now the science director of the national Ocean Research Interactive Observatory Network. In his spare time, Ken enjoys travel and historic railroads.

Where the Rivers Meet the Sea

The transition from salt to fresh water is turbulent, vulnerable, and incredibly bountiful

By Rocky Geyer, Senior Scientist and Chair
Applied Ocean Physics & Engineering Department
Woods Hole Oceanographic Institution

The sea lions stop bellowing and slip, one by one, off the jetty into the mocha-brown water of the Fraser River near Vancouver, British Columbia. The surface of the water is smooth, except for a line of ripples moving slowly upriver. The sea lions seem to know that the calm surface belies turmoil beneath.

The tide has just turned, and a tongue of salt water is first creeping, then galloping, back into the Fraser just a few hours after being expelled by a strong outflow during the previous ebb. Although the surface appears calm, the underwater intersection of fresh and salt water roils with turbulent eddies as strong as any in the ocean. The confusion of swirling water and suspended sediments disorients homeward-bound salmon, providing an easy feast for the sea lions.

Not all rivers end as dramatically as the Fraser. But the mixing of freshwater streams and rivers with salty ocean tides in a partly enclosed body of water—scientists call it an estuary—fuels some of the most productive ecosystems on Earth, and also some of the most vulnerable.

Long before the advent of civilization, early humans recognized the bounty of the estuary and made these regions a focal point for human habitation. Unfortunately, overdevelopment, poor land use, and centuries of industrial contamination have taken a toll on most estuaries. Boston Harbor, San Francisco Bay, and the Hudson River are poster children for environmental degradation.

Yet there is hope. Estuaries are the borderlands between salt- and freshwater

Rocky Geyer, WHOI

MIXING IT UP IN GOTHAM—WHOI Senior Research Assistant Jay Sisson (left) and Engineer Craig Marquette maneuver a box corer after plucking a 30-centimeter-deep sample of sediment from the bottom of the Hudson River in June 2001. Within sight of Manhattan, the researchers measured the rate at which sediment accumulates along this intersection between salty ocean water and fresh river water.

environments, and they are incredibly diverse both biologically and physically. The diversity and the high energy of the ecosystem make estuaries remarkably resilient. With a better understanding of these systems, we can reverse their decline and restore the ecological richness of these valuable, albeit muddy, environments.

How does an estuary work?

From a physicist's point of view, the density difference between fresh and salt water makes estuaries interesting. When river water meets sea water, the lighter fresh water rises up and over the denser salt water. Sea water noses into the estuary beneath the outflowing river water, pushing its way upstream along the bottom.

Often, as in the Fraser River, this occurs at an abrupt salt front. Across such a front, the salt content (salinity) and density may change from oceanic to fresh in just a few tens of meters horizontally and as little as a meter vertically.

Accompanying these strong salinity and density gradients are large vertical changes in current direction and strength. You can't see these swirling waters from the surface, but a fisherman may find that his net takes on a life of its own when he lowers it into seemingly placid water.

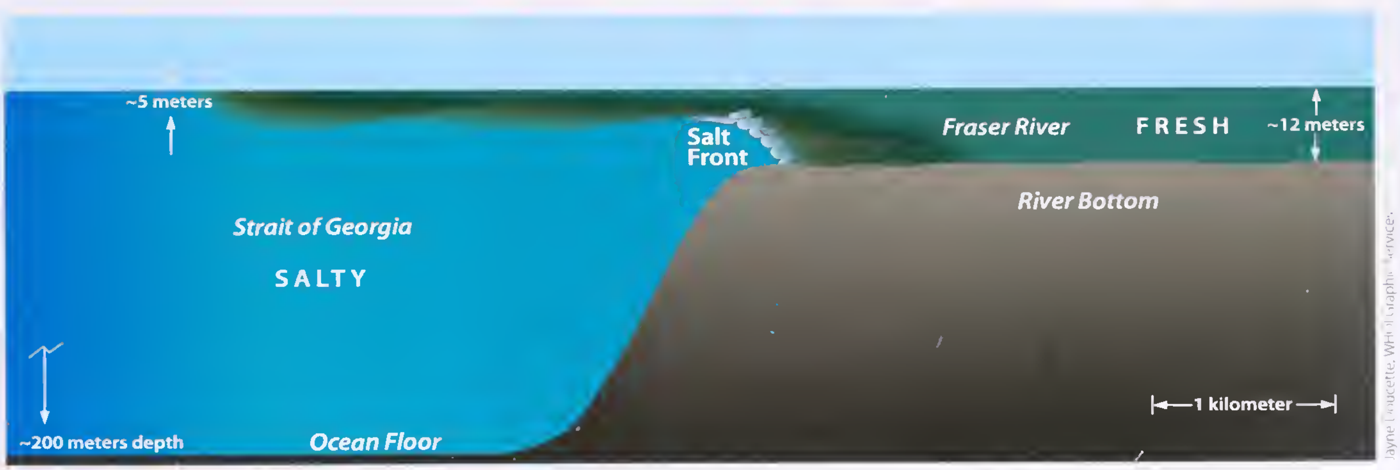
Pliny the Elder, the noted Roman naturalist, senator, and commander of the Imperial Fleet in the 1st century A.D., observed this peculiar behavior of fishermens' nets in the Strait of Bosphorus, near Istanbul. Pliny deduced that surface and bottom currents were flowing in opposite directions, and he provided the first written documentation of what we now call the "estuarine circulation."

FLOOD OF ACTIVITY—A satellite image shows plumes of sediment suspended in the waters of the Fraser River as they pour into the Strait of Georgia in June 2003. The mixing of Rocky Mountain and Pacific waters creates one of the world's most productive estuaries.

Saltwater intrusion

The opposing fresh and saltwater streams sometimes flow smoothly, one above the other. But when the velocity difference reaches a certain threshold, vigorous turbulence results, and the salt and fresh water are mixed. Tidal currents, which act independently of estuarine circulation, also add to the turbulence, mixing the salt and fresh waters to produce brackish water in the estuary.

In the Fraser River, this circulation is confined to a very short and energetic frontal zone near the mouth, sometimes only several hundred meters long. In other estuaries, such as San Francisco Bay, the Chesapeake Bay, or the Hudson River, the salt front and accompanying estuarine



A COASTAL MIXING BOWL— Nutrient- and sediment-laden fresh water from the Fraser River in British Columbia rides up and over salty ocean waters, which are beginning to march upriver during flood tide. The interaction of the two water masses of different salinities and densities in the estuary creates underwater turbulence and mixing that naturally flushes and energizes the coastal system.

circulation extend inland for many miles.

The landward intrusion of salt is carefully monitored by engineers because of the potential consequences to water supplies if the salt intrusion extends too far. For instance, the city of Poughkeepsie, N.Y., 60 miles north of the mouth of the Hudson River, depends on the river for its drinking water. Roughly once per decade, drought conditions cause the salt intrusion to approach the Poughkeepsie freshwater intake. The last time this happened, in 1995, extra water had to be spilled from dams upstream to keep the salt front from becoming a public health hazard.

The lifeblood of estuaries

Estuarine circulation serves a valuable, ecological function. The continual bottom flow provides an effective ventilation system, drawing in new oceanic water and expelling brackish water. If it weren't for this natural "flushing" process, the waters of the estuary would become stagnant, pollution would accumulate, and oxygen would be depleted.

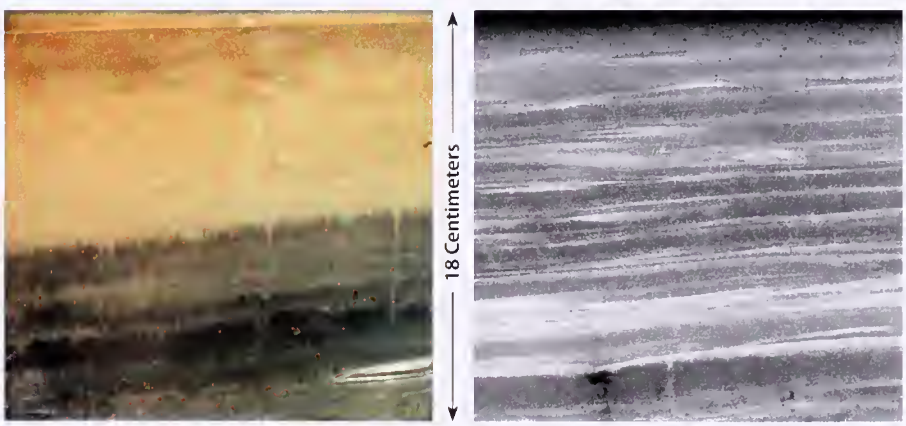
This circulation system leads to incredible ecological productivity. Nutrients and dissolved oxygen are continually resupplied from the ocean, and wastes are expelled in the surface waters. This pumping action leads to some of the highest growth rates of microscopic plants (researchers call it "primary production") in any marine environment. This teeming population of plankton provides a base for diverse and valuable food webs, fueling the growth of some of our most prized fish, birds, and mammals—salmon, striped bass, great blue heron, bald eagles, seals, and otters, to name a few.

The vigor of the circulation depends in part on the supply of river water to push the salt water back. The San Francisco Bay area has become a center of controversy in recent years because there are many interests competing for the fresh water flowing into the Bay—principally agriculture and urban water supplies extending to Southern California. Environmentalists are determined that San Francisco Bay should get "its share" of the fresh water coming from the Sacramento-San Joachim delta because the vast freshwater habitats in the region are particularly vulnerable to salt intrusion.

Estuarine circulation is also affected by the tides; stronger tides generally enhance the exchange and improve the ecological function of the system. The Hudson estuary, for example, is tidal for 153 miles inland to Troy, N.Y. The Algonquin Indians called the river Mohicanituk, "the river that flows both ways."

Mucking up the system

Estuaries have their problems. Some are self-inflicted; some are caused by the abuses of human habitation.



Chris Sommerfield University of Delaware

SEEING THROUGH MUD—Photograph (left) and x-ray image (right) of sediments from a region of rapid deposition in the Hudson River estuary. The sharp change in color (left) indicates a change from fresh, oxidized sediment to older, anoxic mud. X rays reveal laminations of silt (light colors) and mud (dark) formed by repeated deposition and erosion over tidal cycles.

An estuary, with all of its dynamic stirrings, has one attribute that promotes its own destruction: It traps sediment. When suspended mud and solids from a river enter the estuary, they encounter the salt front. Unlike fresh water, which rides up and over the saline layer, the sediment falls out of the surface layer into the denser, saltier layer of water moving into the estuary. As it drops, it gets trapped and accumulates on the bottom. Slowly, the estuary grows muddier and shallower.

Occasionally a major flood will push the salt out of the estuary, carrying the muddy sediment along with it. Sediment cores in the Hudson River indicate that sediment may accumulate for 10, 20, or even 50 years, laying down layers every year like tree rings. But then a hurricane or big snowmelt floods the river, wipes out the layers of sediment, and sends the mud out to sea.

The "episodic" behavior of sediment deposition is good news and bad news. It is good because a big storm can keep an estuary from getting too shallow too fast. In fact, it appears that over the last 6,000 years, the natural dredging by large storms has maintained nearly constant water depth in the Hudson estuary.

The bad news is that the sediment retains a "memory" of all of the contaminants that have passed through it over the years. Environmental regulations are far stricter now than they were 50 years ago, and we have stopped using many chemicals that play havoc with the environment. For instance, polychlorinated biphenyls (PCBs) were banned in the 1970s because they were shown to be toxic to fish and wildlife, and to the humans who consume them. Yet we still have a contamination problem in the Hudson and other rivers because PCBs are slow to decay and each new flood remobilizes these "legacy" contaminants and prolongs our exposure.

Trickle-down effects

Billions of dollars are now being spent to clean up American estuaries contaminated by industrial pollution. In Boston,

Rocky Geyer, WHOI

GETTING DIRTY AT WORK—WHOI Assistant Scientist Peter Traykovski (left), Senior Research Assistant Jay Sisson, and a professional diver examine an instrument tripod covered with hydroids and mud after six months on the bottom of the Hudson River. Researchers chronicled currents, the flow of sediments, and changes in river bed elevation due to erosion and deposition.

for instance, the new sewage system created to clean up Boston Harbor cost taxpayers about $5 billion. The Superfund program of the U.S. Environmental Protection Agency collects and spends billions of dollars more to remediate estuaries.

Often the remediation strategies are complex and controversial. In the case of Hudson River, there is a heated debate about whether PCB-contaminated sediments should be removed—dredged with high-tech methods that theoretically minimize environmental harm—or left undisturbed. That debate pivots on the episodic storm phenomenon: Are the contaminated sediments there to stay, or could they get stirred up when the next hurricane washes through the Hudson Valley?

Aside from cleanup initiatives, parts of the Hudson need to be dredged for navigational purposes. Dredging is not that costly or difficult, but finding a place to put contaminated sediments is a problem. The Port of New York has been filling up abandoned Pennsylvania coal mines with its contaminated mud, but that is not a long-term solution.

While the problems of American estuaries are complicated and expensive, they pale in comparison to Asian estuaries. The entire nation of Bangladesh lies within the estuary and lower floodplain of the Ganges-Brahmaputra River. Other Asian rivers such as the Mekong, Chiang Jiang (or Yangtze), and Huang Ho (or Yellow River) are crowded and strained by concentrated human settlements. Global sea-level rise is causing a loss of land, increased flooding, and increased salt intrusion in these estuaries.

The demand for water upstream for irrigation and domestic use significantly reduces freshwater flow through these systems. The Indus River and Huang Ho estuaries have suffered from drastic reductions of freshwater flow over the past several decades, and the impact of these human alterations is just now being recognized. New policies about land use, water diversion, and even global carbon dioxide production (which affects global warming and sea level rise) will be needed to protect these vulnerable estuarine environments and their human inhabitants.

Stirring up new ideas

One of the challenges of estuarine research is that most of the significant problems are interdisciplinary, involving physics, biology, chemistry, geology, and often public policy and economics. Estuaries are also incredibly diverse, coming in all shapes and sizes. Yet scientists are continually challenged by public policymakers to generalize our results from studies of one estuary and apply them to the rest of the world's estuaries.

As scientists, one of our roles is to predict changes in the environment, given different natural and human-induced influences. To foresee the health of estuaries in the future, we have some fundamental questions to answer about the present and the past. How far will salt intrude if river flow is cut in half? Do changes in river flow increase or decrease the rate at which sediments shoal the estuary? What effect do such changes have on the fish that spawn in fresh water?

What we learn will be critical for a human population that increasingly values coastal waters. We need sound public policy to reduce vulnerability to coastal flooding and to protect drinking water, food supplies, and some of the world's most important habitats. We will develop better policies only if we can ground them in better science.

Terry Donoghue, WHOI

Rocky Geyer is the former director of WHOI's Rinehart Coastal Research Center. He earned a bachelor's degree in geology from Dartmouth College and master's and doctoral degrees in physical oceanography from the University of Washington. Geyer was a sailor before he was a scientist, and he was long baffled by the complex swirls of currents that often wrecked havoc with his attempts at precision navigation. He had the good fortune to turn this fascination into a vocation, and has subsequently worked in many estuarine and coastal environments, including the Amazon outflow, the Po River outflow in Italy, the fjords and estuaries of the Pacific Northwest, the tidal channels of New England and Singapore, the Hudson River, the Eel River plume in northern California, and the western Gulf of Maine. Geyer's research includes a blend of observational process-studies and numerical modeling, directed both at basic research questions and applied problems of societal concern, such as harmful algal blooms and contaminant transport. Geyer has served on the National Research Council's Panel on Environmental Processes: Source, Fate and Transport, and is a member of the Ocean Studies Board.

Rites of Passage for Juvenile Marine Life

Learning from the life-or-death journeys of barnacle, lobster, and clam larvae

By Jesús Pineda, Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

The childhood of a barnacle is fraught with challenges. It hatches in shallow waters close to shore as a tiny larva, no bigger than a speck of dust. Currents sweep it to deeper, choppy waters, sometimes miles offshore. In these proving grounds each larva floats, at the mercy of hungry fish and swift ocean currents.

Billions of larvae—including fish, lobsters, clams, starfish, and sea cucumbers—begin life this way. Only a few survive and return to shore, where they settle on rocks or sandy seafloor to become adults.

Why larvae make their offshore journey remains unclear, but we are beginning to uncover the intricacies of their return trip—learning how waves, currents, eddies, tides, and other phenomena bring larvae back toward the shore. With more insight into the ocean's role in this essential phase in the life cycle of these species, natural resource managers can devise better strategies to sustain healthy, vibrant habitats for marine life.

For example, ocean circulation may explain why populations of lobsters or clams are sparse in some rocky coastal habitats that appear ideal. Prevailing ocean currents may never deliver larvae to their promised land. Similarly, it would be futile for coastal managers to create marine reserves or shellfish beds in areas where larvae are doomed by currents to be carried so far offshore that they cannot return.

Telltale clues in murky waters

My interest in larval research was sparked in 1988 during a scuba diving class in La Jolla, Calif., where I had just be-

Jesús Pineda, WHOI

A CLOSE LOOK AT BARNACLES—Tracy Pugh, a former research assistant in the WHOI Biology Department, records the growth of barnacles in Buzzards Bay on Cape Cod, Mass. Understanding how juvenile barnacles and other marine invertebrates are transported by waves, currents, eddies, tides, and other phenomena helps researchers devise strategies to sustain vibrant habitats.

Fabian Tapia, WHOI
Todd Stueckle, WHOI
Vicke Starczak, WHOI

LIFE WITH LARVAE—LEFT: Hair-like appendages on this two-week-old barnacle larva churn the water to aid in feeding. CENTER: After four to seven weeks, juvenile larvae settle along the shore and develop a hard white shell. RIGHT: Adult barnacles, about one year old, form plates to hold their body together and for protection.

gun my doctoral studies at Scripps Institution of Oceanography. During a dive close to shore, I spotted a layer of brown water about 10 meters (33 feet) down. When I swam into it, the water felt very cold.

The next day I returned and swept a net through this brown water. When I analyzed my catch in the lab, I found the color came from patches of maturing larvae ready to settle near the shore. These observations hinted at a mechanism for transporting larvae toward the beach.

Near the coast, warm fresh water often collides with colder, saltier water. These different bodies of water have different densities, so they tend to remain relatively distinct. In many ways, the boundary between these water masses behaves like the boundary between two other "fluids"—the sea surface and the atmosphere. Just as waves form and propagate on the ocean surface, waves also form within the ocean, along the boundaries between warm, light water and cold, dense water.

My observations in scuba diving class suggested that larvae were being transported toward shore in cold-water waves moving below the sea surface. But these waves, called internal bores, told only half of the story.

Coastal fronts

I spotted evidence for the other half of the puzzle on my way home from a seaside party. Looking at the Pacific Ocean, I saw lines of foam, seaweed, and plastic debris forming parallel to the shore and stretching several hundred feet across the sea surface. Most beachgoers have probably seen these features, which form at the intersection where warm and cold water masses meet. Scientists call them coastal fronts.

The full picture of the larval transport process fell into place. As ebbing tides move water over seafloor obstacles, they create internal bores, which transport large volumes of cold water from deep offshore areas toward the shore. The incoming wave of cold water pushes warmer nearshore waters out to sea. A few hours later, the heavier cold water sinks and recedes offshore. Warmer, lighter water near the surface surges inshore and over the receding cold water, led by a vanguard of coastal fronts. Along with kelp and debris, the coastal fronts carry larvae ashore.

A rare wave within the ocean

In the years since those observations, I have studied various phenomena involved in larval transport along the coasts of southern California, northwestern Mexico, and Massachusetts. With funding from the National Science Foundation and the Office of Naval Research, I have investigated why some types of larvae accumulate in fronts, while others do not. I also have examined whether periodic ocean circulation changes such as El Niño have an impact on larval transport.

Many puzzles remain. For example, we know little about how currents in the nearshore environment connect with larger oceanic currents. If larvae are swept far from the shore of their birth, do they grow up somewhere else or are they lost altogether?

And while our work on internal bores has focused on larvae, other researchers have been interested in whether this process transports offshore deposits of sewage and nutrients back onto the beach.

Recent research has shown that internal waves come in various flavors with varying impacts on larvae. (Internal bores are but one flavor.) I am currently collaborating with Alberto Scotti, who studies fluid dynamics at the University of North Carolina, to investigate a rare type of internal wave in the ocean called a "wave of elevation." As the name suggests, these waves have taller crests than others around them. Within each wave of elevation a strong circular flow of water moves horizontally, spinning any trapped particles like clothes in a washing machine.

These waves are rarely observed in nature, but we identified some in Massachusetts Bay. We suspect they may influence how larvae move to their adult settlements. As the wave moves toward land, larvae may become caught up in this rotation and concentrate together.

To test this, we are planning to conduct an experiment where we will deploy plastic-covered electronic drifters (about the size of soda cans) in areas with waves of elevation. We will record information about buoyancy and particle accumulation in the hope of finding out what larvae must do to catch a ride on these waves.

MIT/WHOI Joint Program student Fabián Tapia (left) and WHOI Postdoctoral Scholar Claudio DiBacco use fine nets to sample patches of cypris barnacle larvae floating in Narragansett Bay, R.I. Larvae ride internal bores—wave fronts beneath the surface of the ocean—toward the shore when they are mature enough to settle on rocks and coastal structures.

Photos by Jesús Pineda, WHOI

Surfing to turf

I have also conducted experiments in the controlled environment of the laboratory to mimic what I saw in the sea. With funding from the WHOI Rinehart Coastal Research Center, I collaborated with WHOI physical oceanographer Karl Helfrich, who studies the mechanics and fluid dynamics of the coastal ocean.

We used a rectangular tank bisected with a Plexiglas dam, filling one side with lighter fresh water, dyed blue, and the other side with heavier, saltier water. We added buoyant, peppercorn-sized nylon beads (representing larvae) to the fresh water. When we lifted the dam, a tongue of blue-dyed fresh water surged across the surface of the salty water. We watched as the beads accumulated behind this freshwater tongue.

Applied to the coastal zone, this experiment suggests that some species of larvae may accumulate behind—not in front of—coastal fronts and internal bores. These larvae surf the waves toward shore. However, we also found that the larvae of other species may be pushed ahead of an incoming front, like the dirt piled up in front of a bulldozer.

Swimming against the current

Whether larvae are pushed or pulled onshore turns out to make a difference. The collision of water masses of different densities creates powerful downward-flowing currents that threaten to sweep larvae into the depths. The larvae must resist this downward pull and continue moving forward.

They do this by swimming. Several weeks into their growth cycle, larvae develop appendages to swim. Some organisms, such as sea anemones, develop cilia—wiggly, hair-like protrusions that work like oars. Other species such as barnacles grow a single strong leg that functions like a flipper.

With Karl Helfrich and Claudio DiBacco, a larval ecologist at the University of British Columbia, I am now using a specially designed experimental chamber to determine how larvae swim when downward currents flow against them. We are interested because those larvae that do not swim fast enough will be left behind by the traveling front and will not reach the shore. Karl and I also have found that in order to resist the downward drag, larvae swimming ahead of a front have to swim faster than those swimming behind.

The challenges confronted by larvae do not end near land. We are also interested in what happens to them once they arrive close to shore. Frequently my colleagues and I leave our microscopes and laboratories and head to beaches, coastal lagoons, and rocky coastlines to study how larvae accumulate and mature. Some areas host thick carpets of juvenile organisms. Others have none at all.

In 2003, I visited a new research facility along the Pacific coast of Panama known as the Liquid Jungle Lab. While exploring a nearby estuary, I examined a clump of mangrove roots. The rocky, remote, and relatively pristine sanctuary is a habitat rich with food, so I suspected it would be equally rich with marine species. Yet I found surprisingly few organisms.

Very few people live near the lab, so it's unlikely that pollution prevented colonization of the mangrove roots. I suspect that as rainforest leaves fall and rot, they leach naturally occurring chemicals into the coastal zone and kill any larvae. I plan to return and test this hypothesis because, despite their small size, larvae teach me a lot about life in our oceans.

—WHOI Science Writer Amy E. Nevala contributed to this article.

Tom Kleindinst, WHOI

As a boy, Jesús Pineda traveled each summer from his home in Mexico City to his grandmother's ranch in central Mexico, where he fished for catfish from a local river. That interest spurred a biology and oceanography career, and he quickly found barnacles, sea anemones, clams, and other creatures without backbones more intriguing than fish. After earning degrees in biological oceanography and marine ecology at Escuela Superior de Ciencias Marinas and at Centro de Investigación Científica y de Educación Superior de Ensenada in Mexico, he completed doctoral studies in oceanography at the Scripps Institution of Oceanography. He joined WHOI as a postdoctoral scholar before becoming an associate scientist in 1998. For his research, he has explored coastlines in the United States, as well as Mexico, Chile, and Panama.

Water Flowing Underground

New techniques reveal the importance of groundwater seeping into the sea

By Matthew Charette, Associate Scientist
Marine Chemistry and Geochemistry Department
and Ann Mulligan, Assistant Scientist
Marine Policy Center
Woods Hole Oceanographic Institution

Up in the cliffs, Nickerson had noticed the…display of 'extraordinary spirit and activity' and soon became part of a general rush for the beach. The men had, in fact, found a spring bubbling up from a hole in a large flat rock…once everyone had been given a chance to drink, they began to marvel at their good fortune. The spring was so far below the tide line that it was exposed for just a half-hour at dead low; at high tide it was as much as six feet underwater. They had time to fill only two small kegs before the rock once again disappeared below the surf.

—*In the Heart of the Sea: The Tragedy of the Whale Ship Essex* by Nathaniel Philbrick

The story of the 1820 sinking of the whaler *Essex*, which was rammed by a sperm whale, inspired Herman Melville's *Moby Dick*. It also provides an inspirational story of how geology came to the rescue of shipwrecked men.

Cut adrift in longboats in the middle of the Pacific, the eight survivors of the disaster—including 14-year-old Thomas Nickerson—headed toward South America. When they finally reached land, the dehydrated sailors had the good fortune to find fresh groundwater pouring out of the beach face at low tide. That water saved their lives.

It turns out that Nickerson's fortunate observation is not that unusual. Nearly 97 percent of the world's usable freshwater lies underground, and the contents of that vast underground reservoir sometimes seep into the ocean. In fact, wherever aquifers are hydraulically connected to the ocean, submarine groundwater can discharge into the sea and saltwater can

Tom Kleindinst, WHOI Graphic Services

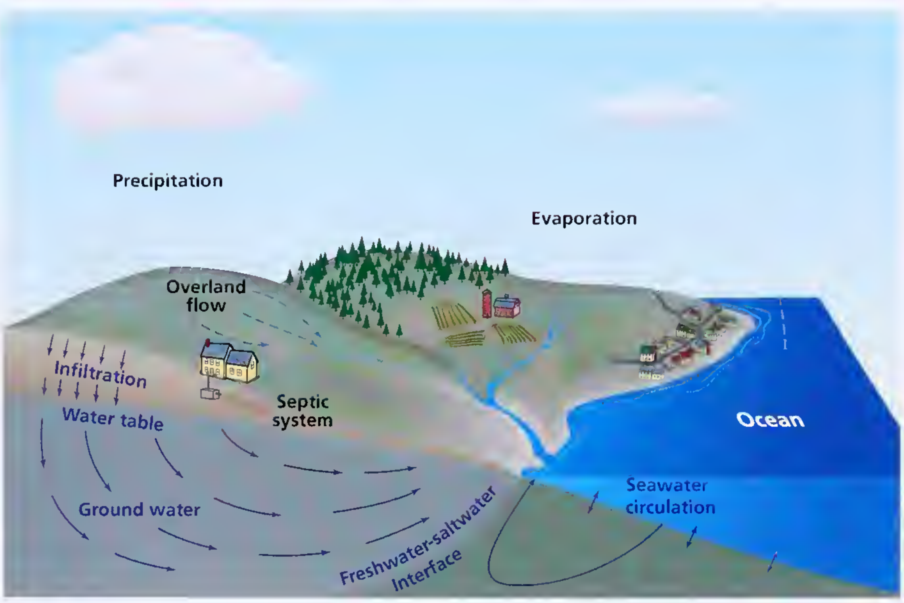
FINDING WATER BENEATH THE WATER—WHOI Postdoctoral Scholar Kevin Kroeger and Guest Student Kayla Halloran install a well in Eastham, Mass., to sample groundwater seeping into a salt pond. Between 5 and 10 percent of the fresh water in the ocean comes from groundwater.

intrude landward into fresh aquifers.

Because most humans have a predilection for living along the coast, groundwater-seawater interactions have become increasingly important to understand. Pertinent questions include: How much groundwater is flowing from land to sea? What is that water carrying with it? How do human activities affect groundwater quality and the coastal ecosystem?

Historically, coastal groundwater studies were focused on saltwater intrusion into inland freshwater aquifers, which can have dire consequences for drinking water supplies. Little attention was paid to submarine groundwater discharge to the coastal ocean because scientists thought it was insignificant compared to the discharge from rivers and other surface waters. Statistically, they were right: Groundwater represents about 5 to 10 percent of the freshwater input to the ocean.

In recent years, however, submarine groundwater discharge has received more attention because new research shows that it is more than just a simple exchange of water between land and sea. The flow of groundwater into the ocean is critical because those fluids often carry a substantial amount of dissolved nutrients and pollutants. The appearance of cloudy, algae-filled water in some harbors and bays may be the result of this out-of-sight nutrient input.

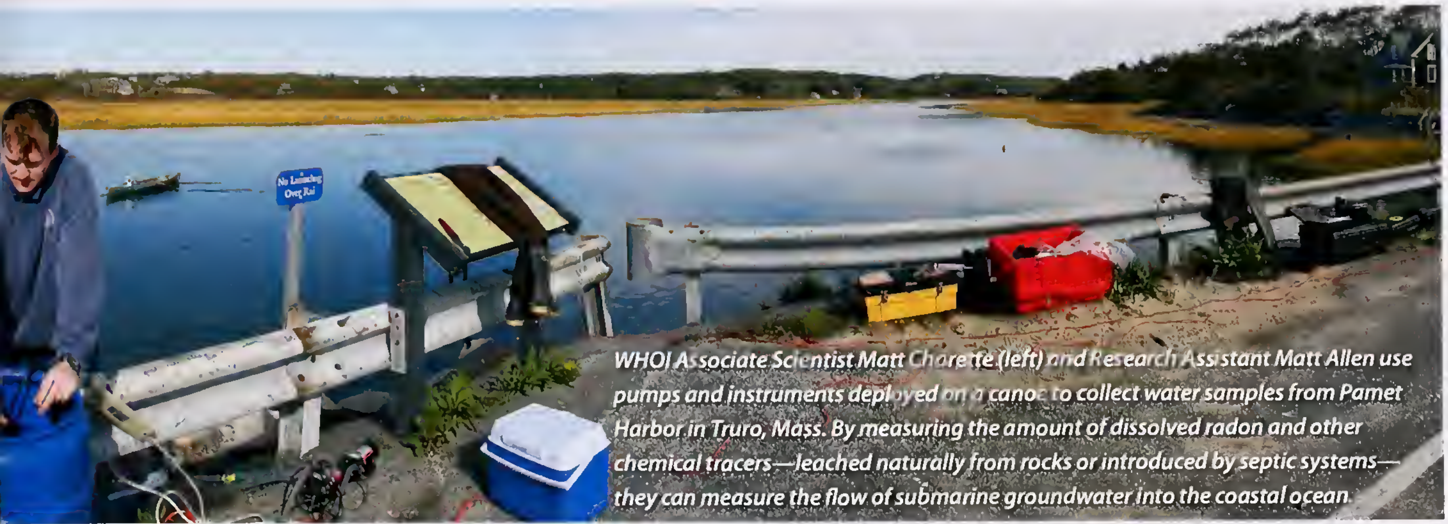


HYDROLOGIC CYCLE IN COASTAL ZONES—Precipitation either evaporates into the atmosphere, gets taken up by plants, flows into streams, or infiltrates the ground and recharges aquifers. Groundwater flows from inland locations to lakes, streams, or coastal waters. On the seaward side, denser salt water enters sediments and establishes equilibrium with fresh groundwater. Tides and mixing along the freshwater-saltwater interface results in seawater circulation through the sediments.

Water dissolving, water removing

Groundwater discharge appears to be an important factor for determining the chemistry of the coastal ocean. As fresh groundwater flows toward the sea, it rises up over denser, salty water. The fresh and salty water mix along the interface, and the resulting fluid discharges at the shoreline. This interface between underground water masses has recently been described as a "subterranean estuary," a mixing zone between fresh and salty water analogous to the region where a river meets the ocean. (See "Where the Rivers Meet the Sea," page 22.)

A variety of reactions and transformations both inland and near the coast can influence the amount of dissolved chemicals passing through this underground estuary. Nitrogen, phosphorous, and other contaminants may be introduced into groundwater through a variety of mechanisms. Wastes and nutrients leach from



WHOI Associate Scientist Matt Charette (left) and Research Assistant Matt Allen use pumps and instruments deployed on a canoe to collect water samples from Pamet Harbor in Truro, Mass. By measuring the amount of dissolved radon and other chemical tracers—leached naturally from rocks or introduced by septic systems—they can measure the flow of submarine groundwater into the coastal ocean.

Tom Kleindinst, WHOI Graphic Service

septic systems. Rainfall carries atmospheric pollutants and ground spills down through the soil. Eventually, these chemicals flow underground toward the ocean just as they do in surface tributaries.

Once these dissolved chemicals reach coastal waters, they can influence the abundance of plants and other living species. It is not unusual, for instance, for groundwater to contain dissolved nitrogen in concentrations 100 to 1,000 times greater than in seawater. Nitrogen from human sources, for instance, has led to the over-enrichment (eutrophication) of many coastal bays and waterways. (See "Red Tides and Dead Zones," page 43.)

Under the rocks and stones

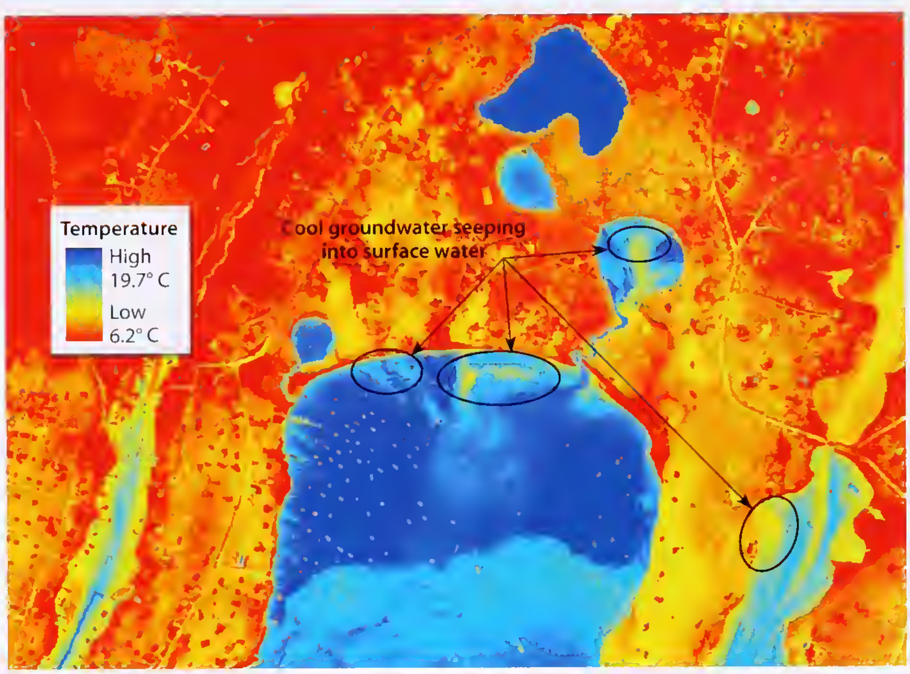
Groundwater often flows for long distances and time scales. Unlike surface estuaries, in which water is restricted horizontally by topography—for instance, hills and banks restrict water to channels or streams—groundwater flows throughout Earth's crust. Soil and subsurface geology play a vital role in influencing the direction and rate at which groundwater flows.

The patterns of submarine groundwater discharge are the result of complex interactions between hydrologic, chemical, geologic, and human influences. A variety of disparate techniques have been developed for accurately assessing and predicting these flows. Unraveling this knot of interwoven influences requires scientists to work across disciplines, bringing chemists together with geologists, hydrologists with mathematical modelers.

For instance, models are useful for investigating and integrating the complexities of the groundwater discharge system, and for predicting the effect of human activities. Models offer idealized mathematical descriptions of how hydrology and underground geology can affect flow. But grounding these models in reality requires a reasonably accurate three-dimensional map of the underground geology.

Such maps require field sampling and the drilling of boreholes into the ground, which can be invasive and expensive. Data from boreholes are high in resolution—scientists can "see" features in the subsurface that are as small as a centimeter—but each hole in the Earth represents a very small sample of sediment at only one location.

Researchers also use geophysical techniques such as ground-penetrating radar, electromagnetic resistivity, and seismic



SensyTech, Inc. and Ann Mulligan, WHOI

COOL VIEW OF GROUNDWATER—Infrared images shot by airplane in September 2002 reveal the extent of groundwater seeping into Waquoit Bay, Mass. Bright yellows indicate locations where cool groundwater is emerging from the sandy bottom into the salty, warm waters of the bay.

Tom Kleindinst, WHOI Graphic Servi...

GO WITH THE FLOW—WHOI Assistant Scientist Ann Mulligan (foreground), Research Assistant Meagan Gonneea (blue shirt), and visiting student Claudette Spiteri collect data about groundwater discharge into Waquoit Bay, Mass. By measuring water pressure, temperature, and conductivity, they can monitor how fast groundwater is flowing and how the interface between fresh water and salt water changes over time.

studies, which use the magnetic and sound-propagating properties of rocks and sediments to survey broad areas beneath the surface. Such technological approaches are now less expensive, less invasive of the environment, and more likely to map large areas quickly.

But these tools only provide knowledge of specific physical properties of the underground geology; they do not tell us what types of sediments are below the surface. For that, we must have direct samples (as obtained by drilling) that we can then correlate to the geophysical data.

The best way to map the subterranean environment and its effect on groundwater flow is to combine techniques. By drilling boreholes and conducting geophysical surveys, we can amass enough data to draw realistic maps of the subsurface, which, in turn, make our models more realistic.

Water at the bottom of the ocean

As we develop maps of the underground landscape, we can also gain insight about the groundwater system if we can see precisely where the groundwater is entering the sea, how much is flowing out, and how fast the groundwater is moving. Airborne thermal imaging—which exploits the temperature contrast between groundwater and surface water—is proving to be an especially useful tool for locating groundwater discharge.

On Cape Cod, for example, groundwater maintains a temperature between 10° to 15°C throughout the year; ocean surface water varies from 25°C in summer to 0°C in winter. Through the use of infrared cameras on planes and blimps, we can detect this thermal contrast and see where groundwater is discharging (see image on page 31). With this information, we can correlate the groundwater discharge pattern with what we know about hydrologic and geologic features. The combination of observations offers clues about what might be controlling the discharge and provides targets for future sampling locations during fieldwork.

Thermal imagery tells the location of submarine groundwater discharge, but not the rate of the flow. To quantify that, researchers have turned to chemical tracers. The concept is relatively simple: In zones of groundwater discharge, we detect and track a chemical in the groundwater that has a different signature or higher concentration than can be found in surface waters. By knowing the concentration of natural tracers in the groundwater, we can estimate how much fluid is required to account for the excess levels observed in the ocean.

The naturally occurring isotopes of radium and radon in Earth's crust have proven to be useful indicators of groundwater discharge. Radium and radon are leached from the rocks and sediments that surround and host groundwater aquifers, and they often become concentrated because they are not cycled or decayed as much as they would be in exposed seawater.

Remove the water, carry the water

There is an old, well-established mechanical approach to measuring groundwater that has recently been given new life: the seepage meter. First conceived in the 1970s, a seepage meter is essentially the top half of a 55-gallon drum placed over the interface where groundwater seeps out

of sediments into the ocean. The seeping groundwater fills a plastic bag connected to the top of the drum, and the amount of fluid captured per unit of time provides an estimate of the flow.

The problem with old-fashioned seepage meters is that they are time- and labor-intensive: If you want to measure flow for 24 hours, you need to sit with your equipment for 24 hours. Longer observations can become tedious, not to mention wasteful when precious research time is spent baby-sitting equipment.

In recent years, we have developed automated seepage meters that allow researchers to track the flow of groundwater continuously for up to a week, even in remote areas. It is now possible to obtain high-resolution, long-term records of submarine groundwater discharge from an unattended, automated meter while we are back in the laboratory working on other parts of the groundwater puzzle. We recently worked with the U.S. Geological Survey to make such measurements as part of their long-term ecosystem rehabilitation program in the Florida Everglades.

Matt Charette, WHOI

AUTOMATED MEASUREMENTS—Research Assistant Matt Allen sits on an airboat and sets up a WHOI-designed automated seepage meter for a three-week deployment in Florida's Everglades.

Into the blue again

Coastal groundwater-seawater interactions have been studied in many parts of the world, including the southeastern coast of the United States, the Mediterranean Sea, Australia, and Cape Cod. In nearly all of those locations, new lines of evidence suggest that submarine groundwater discharge is an important source of dissolved elements to the ocean. However, few comprehensive geochemical studies of such environments have been undertaken.

That is why we are working together as a groundwater hydrologist and a marine chemist. Through interdisciplinary collaboration, we will be able to see a big picture that can get lost in the details of a limited scientific focus. In the coming years, we are planning work with other WHOI geologists, geophysicists, and chemists to broaden our view of the problem by conducting a comprehensive study of an entire groundwater discharge system from offshore to inland.

To advance our understanding of the importance of groundwater to our coastal environment, we must take an interdisciplinary approach. Proper management of coastal water resources—which are becoming overrun by natural and man-made forms of pollution—requires that we learn more about the quantity and quality of these inputs.

The National Science Foundation, the WHOI Coastal Ocean Institute, the Cove Point Foundation, and the National Oceanic and Atmospheric Administration provide funding for this research.

Tom Kleindinst, WHOI Graphic Services

Matt Charette was born in Boston, raised in Lynn, Mass., and spent his summers on the beaches of Truro on Cape Cod (a place he now visits for his groundwater research). Charette earned a bachelor's degree in chemical oceanography from the Florida Institute of Technology and a doctorate in chemical oceanography from the University of Rhode Island. He came to WHOI as a Postdoctoral Fellow in 1998 and was named an Assistant Scientist in 2000. His research focuses on geochemical processes in coastal groundwater and their implications for chemical fluxes to the coastal ocean.

Ann Mulligan earned her bachelor's degree in geological sciences at Brown University, a master's in civil and environmental engineering from Tufts University, and a doctorate in environmental engineering from the University of Connecticut. Her research focuses on water resource management and modeling of groundwater flow and transport. In graduate school, Mulligan concluded that coastal water resources would become an increasingly important issue as development along the coast continues to occur at a rapid pace. She decided to come to WHOI to focus on coastal water resource problems.

The Growing Problem of Harmful Algae

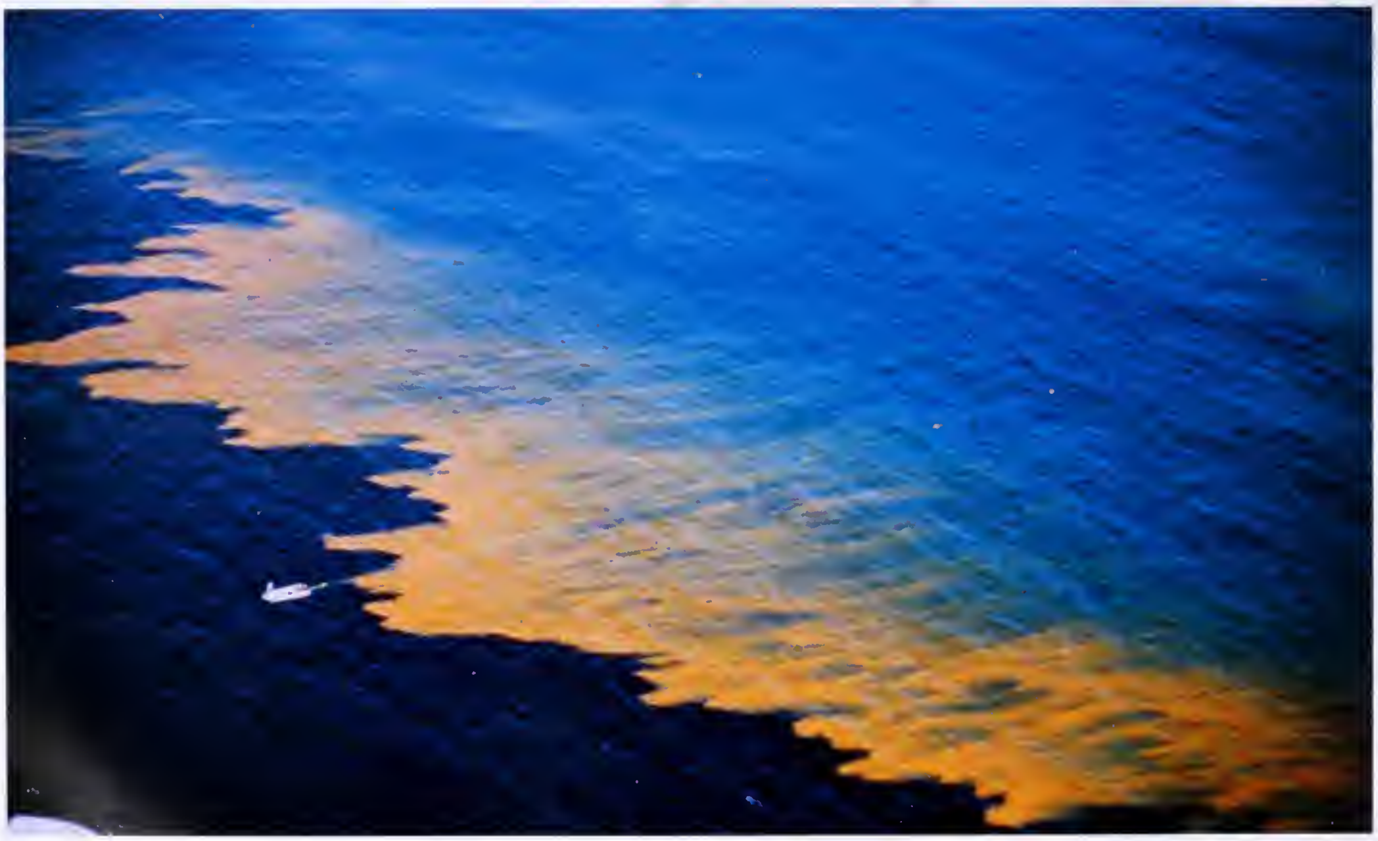
Tiny plants pose a potent threat to those who live in and eat from the sea

By Donald M. Anderson
Director, Coastal Ocean Institute
Senior Scientist, Biology Department
Woods Hole Oceanographic Institution

July and August 2004 — At the height of the summer season, when New Englanders and thousands of tourists open their wallets to buy fresh "steamers" and fried clam strips, Maine's shellfish beds are shut down. Concerned by the worst bloom of toxic algae in 23 years, resource managers closed the flats for fear of paralytic shellfish poisoning. Hundreds of shellfishermen went without income for nearly two months at a time when they typically fill their bushel baskets and wallets. From Nova Scotia to Cape Cod, restaurateurs watched the price of clams jump by 200 percent. All of this was caused by a tiny microscopic organism, Alexandrium, *which does not harm the clams but can sicken or kill humans who eat the shellfish.*

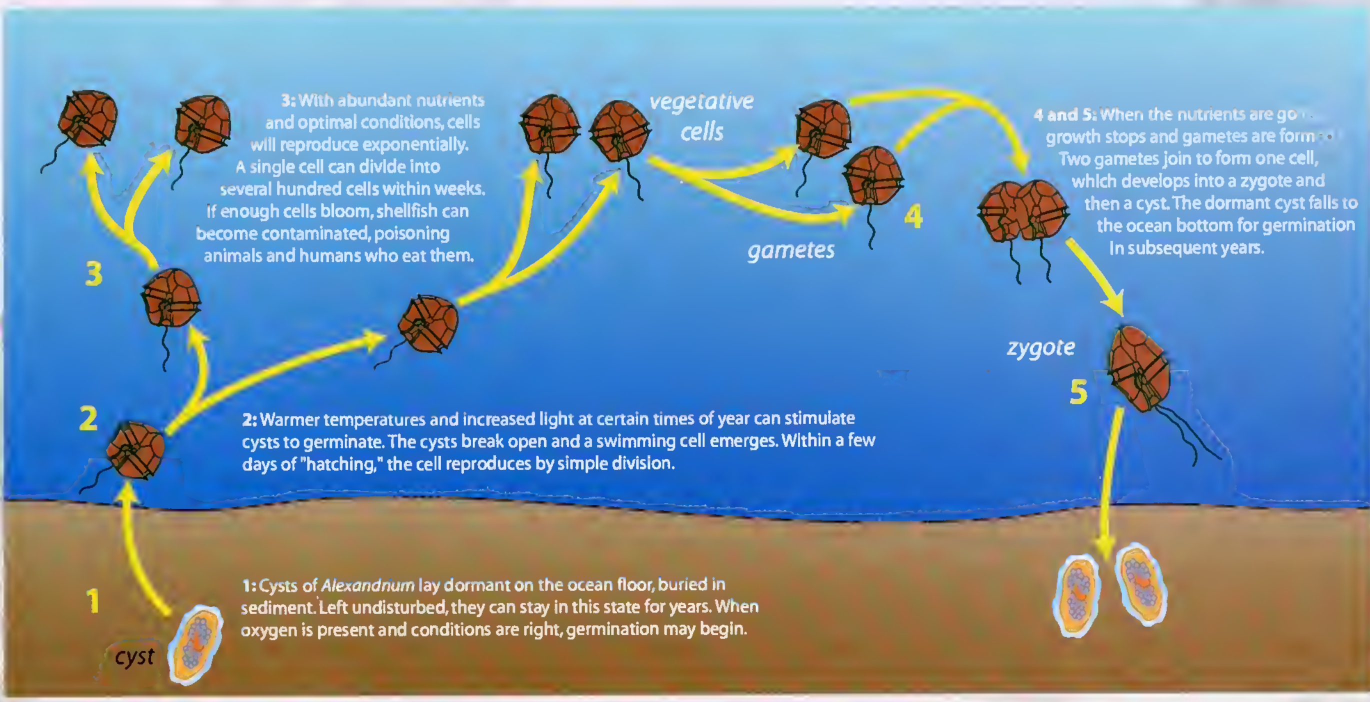
Millions of microscopic plant cells thrive in nearly every drop of coastal seawater. Algae (phytoplankton) are the primary energy producers in the ocean, forming the base of the marine food chain. In the presence of sunlight and a sufficient bath of nutrients, these single-celled plants photosynthesize and multiply, creating a "bloom" that feeds everything from fellow microbes to great fishes.

Among the thousands of species of



Peter Franks, Scripps Institution of Oceanography; background image on spread by D Wall

SEEING RED ALONG THE COAST—A massive "red tide" of blooming algae (the dinoflagellate Noctiluca scintillans*) stretched more than 20 miles near LaJolla, California, in the spring of 1995. Such blooms can have devastating effects on human health, coastal economies, and marine ecosystems. Algal blooms occur naturally, but they have become more common in recent years, some due to human activities that put excess nutrients into the water.*



Don Anderson and WHOI Graphic Services

LIFE CYCLE OF A HARMFUL ALGA—Certain species of toxic algae—in this case, Alexandrium*—have evolved a cyst stage in their life cycle that promotes wide dispersal through the coastal ocean and long-term survival through difficult environmental circumstances.*

algae in the sea, a few dozen produce toxins and pose a formidable natural hazard. Sometimes they reproduce prolifically, discolor the water, and foul beaches with foam from their prodigious population explosions. Other times these harmful algae are dilute and invisible, nearly inconspicuous if not for the destruction they cause. A bloom of harmful algae can completely and permanently alter the structure of a food chain, causing massive die-offs of shellfish, marine mammals, fish, seabirds, and other animals that consume them. They can sicken, disable, or kill humans.

Researchers estimate that blooms of harmful algae cost the United States at least $50 million per year. The economic damage arises from:

- the death of wild and farmed fish, shellfish, submerged aquatic vegetation, and coral reefs
- short- and long-term closure of harvestable shellfish and fish stocks
- reductions in seafood sales, including the avoidance of "safe" seafood due to over-reaction to health advisories
- the costs of conducting monitoring programs to detect and quarantine toxic shellfish and other affected resources
- impacts on tourism and related businesses
- medical treatment of exposed populations.

Harmful algal blooms are natural and they are not new. But ocean scientists are growing concerned that they are now all too common. The unprecedented growth of human activities in coastal watersheds—including agriculture, aquaculture, industry, housing, and recreation—has drastically increased the amount of fertilizer flowing into coastal waters and fueled unwanted algal growth.

A growing plague

And Moses...lifted up the rod, and smote the waters that were in the river, in the sight of Pharaoh, and in the sight of the servants; and all the waters that were in the river turned to blood. And the fish that were in the river died; and the river stank, and the Egyptians could not drink of the water of the river; and there was blood throughout the land of Egypt. — Exodus 7:20-21

Red tides have been known throughout recorded history, but the nature of the global problem in estuaries and coastal waters has changed considerably over the last several decades, both in extent and in public perception.

Virtually every coastal country is threatened by multiple harmful or toxic algal species. Bloom events can cover areas as small as a coastal pond or as large as one million football fields (more than 1,000 square miles).

These blooms of algae are popularly known as "red tides," since the tiny plants can sometimes increase in such abundance that they change the color of the water with their pigments. The term is misleading because non-toxic species also can bloom and discolor the water, and other species are incredibly toxic even when concentrations are low and the water seems clear. Given the confusion surrounding the meaning of "red tide," the scientific community prefers the term harmful algal bloom, or HAB.

One cause for the increasing frequency of HAB events seems to be nutrient enrichment—that is, too much "food" for the

algae. Just as the application of fertilizer to lawns can enhance grass growth, marine algae grow in response to nutrient inputs from domestic, agricultural, and industrial runoff. Nutrient enrichment leads to excessive production of organic matter (including HABs) and a reduction in the amount of life-giving oxygen dissolved in the water, a process known as eutrophication.

Life cycle of a bloom

Fall 1972 — Over Labor Day weekend, Tropical Storm Carrie blows into New England and becomes a Nor'easter, battering the coast with heavy winds and rain. Unbeknownst to scientists, cells of Alexandrium fundyense *(algae native to the Bay of Fundy) are washed south and west by currents stirred by the storm. Several weeks after Carrie, a massive bloom of shellfish-poisoning algae blankets the waters of New England. Before 1972, toxins associated with* A. fundyense *had not been recorded in western New England waters; since then, that species has bloomed nearly every year.*

Algae usually reproduce by asexual fission: One cell grows and then divides into two cells, then two into four, four into eight, and so on. When growth is unchecked by environmental conditions—such as grazing by animals or a shortage of nutrients or light—harmful algae populations can accumulate to visually spectacular but catastrophic levels.

For some species, a decline in available nutrients provokes a switch to sexual reproduction and a new life stage. When they sense that their boom times are coming to an end, the algae form thick-walled, dormant cells called cysts that settle to bottom sediments. These cysts can survive for years, allowing a species to withstand nutrient starvation, extreme winter temperatures, or even ingestion by animals. When favorable conditions resume, the cysts rupture, germinate, and populate the water column with a new generation of photosynthetically active cells primed for another bloom.

The cyst stage represents an effective strategy for survival and dispersal. With every switch into the cyst stage, a bloom can be carried into new waters by ocean currents, fish, or even humans (via ballast water discharge) and then deposited as a "seed" population that colonizes a new area.

Quiet killers

November 1987 — Over a five-week span, 19 humpback whales die in Cape Cod Bay, Mass., a die-off equivalent to 50 years of natural mortality. Unlike stranding events, where seemingly healthy whales swim into shallow water and beach themselves, these humpbacks were dying at sea and washing ashore. Post-mortem examinations showed that the whales had been healthy immediately prior to their deaths; no lesions or infectious pathogens were detected; and many whales had fish in their stomachs as evidence of recent feeding. Alarmed and saddened by the mysterious deaths, the public and the press speculated that they were caused by pollution. Scientists later discovered that the whales had consumed mackerel with an abundance of algal toxins stored in their flesh.

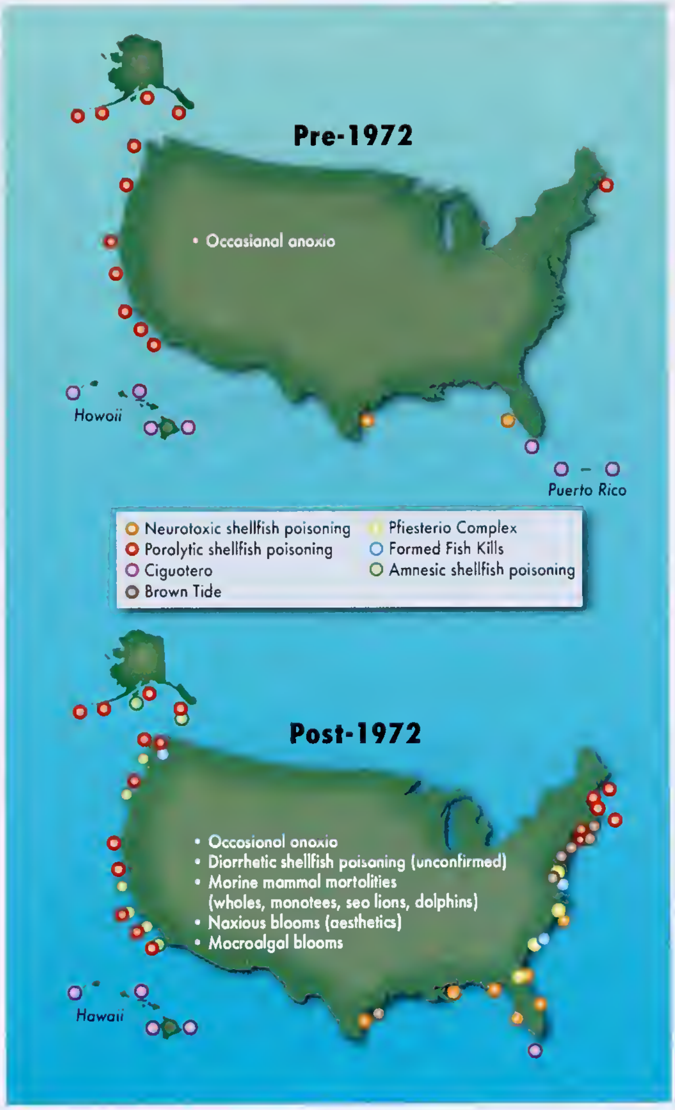
Algal blooms can have an impact even if whales, wild fish, seabirds, and other animals do not consume the microscopic cells. Some algae release their toxins and other compounds into the water, killing creatures through direct exposure. Carnivorous fishes and mammals sometimes die from the cumulative effects of consum-

A COASTAL PLAGUE—Left: A dead humpback whale washed up on the shores of Cape Cod, Mass., as a result of a harmful algal bloom in November 1987. Nineteen seemingly healthy whales died after consuming mackerel laced with an algal toxin. Right: Japanese fish farmers inspect their ruined crop of yellowtail following a devastating red tide in the 1980s.

ing smaller fish or zooplankton containing toxins.

Other HABs kill without toxins. The species *Chaetoceros* has been associated with the deaths of farmed salmon, yet these tiny plants do not produce a toxin at all. Instead they have long, barbed spines that lodge in fish gills, causing a buildup of mucus, degeneration of the respiratory system, and eventual death by suffocation.

Some blooms deplete the resources needed by marine creatures. For instance, when a massive bloom begins to decay, the dying and decomposing algae consume the available oxygen, suffocating other plants and animals or forcing them to migrate. Prolonged blooms of non-toxic algae also can reduce light penetration to the bottom, decreasing the density of aquatic vegetation and grass beds that serve as nurseries for commercially important fish and shellfish. (See "Red Tides and Dead Zones," page 43)



Don Anderson and Jayne Doucette, WHOI Graphic Services

Reports of harmful algal blooms in U.S. waters and around the world have drastically increased in the past three decades. Researchers attribute the increase partly to excessive nutrient pollution of the water and partly to better detection of HABs by coastal monitoring programs.

Blooms of macroalgae (seaweeds) have also increased along the world's coastlines, and they often last longer than typical phytoplankton blooms. Once established, macroalgae can dominate an ecosystem for years and are particularly harmful to coral reefs. Under the right conditions, opportunistic seaweeds outcompete, overgrow, and replace the coral.

These chronic impacts can affect the structure and function of entire ecosystems. The mass die-off of adult fish not only depletes the current population, it prevents breeding-age fishes from reproducing. Larvae or juvenile fish can be stunted or killed, preventing the next generation from reaching maturity.

Such ecosystem degradation likely has long-term consequences for the sustainability or recovery of populations of animals further up the food chain. A population of marine mammals might not grow or reproduce because their main food source has been depleted by HABs. Many researchers now believe that such ecosystem-level effects from HABs are more pervasive than we realize.

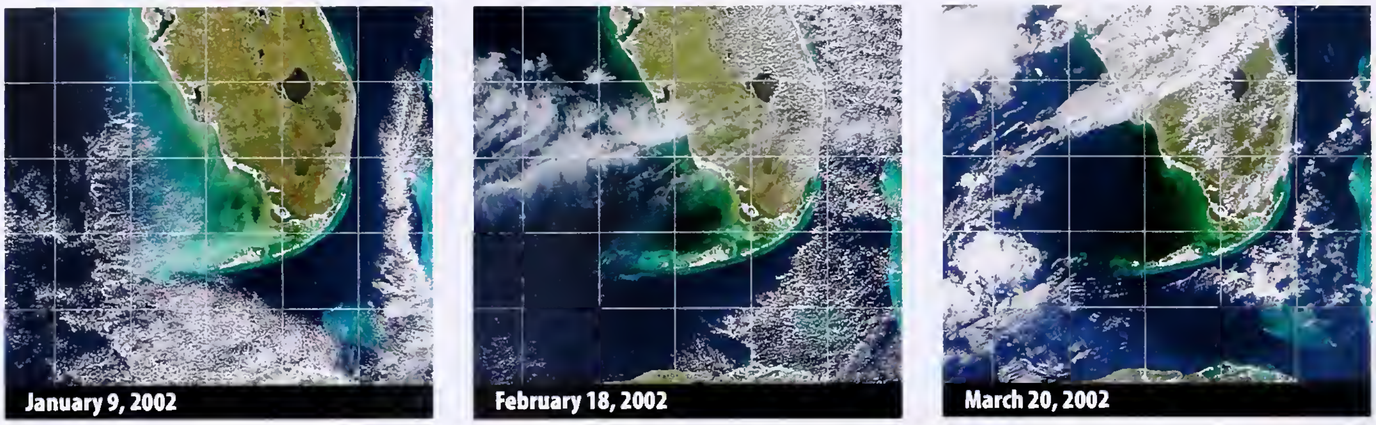
Watch what you eat

February to April 1998—In Hong Kong, where one-third of all finfish consumed comes from fish farms, a devastating HAB wipes out half of the country's annual aquaculture fish stocks. More than 1,500 tons of fish are killed by a neurotoxin-producing alga called Karenia digitatum. *Direct losses are estimated to be HK$250 million ($32 million U.S.). Other fish prices plummet as consumers avoid seafood altogether. A government official calls it the "worst natural disaster" ever to hit Hong Kong.*

Harmful algal blooms can take a variety of forms, each with a distinct and disturbing impact on human health.

• ***Shellfish poisoning***—Most shellfish filter seawater for food. As they eat, they sometimes consume toxic phytoplankton and the algal toxins accumulate in their flesh. The level of toxins can reach a threshold where they become dangerous—sometimes lethal—to humans and other animals, though not to the shellfish themselves. Shellfish poisoning syndromes can cause gastrointestinal and neurological problems, from nausea, vomiting, and incapacitating diarrhea to dizziness, disorientation, amnesia and permanent memory loss, and paralysis. Some syndromes are lethal.

• ***Ciguatera fish poisoning***—Species of the genus *Gambierdiscus* living in tropical waters (particularly coral reef communities) are known to produce a fat-soluble toxin that causes diarrhea, vomiting, and abdominal pain, followed by muscular aches, dizziness, anxiety, sweating, and tingling sensations. Ciguatoxin-producing algae live attached to seaweeds, and they are first consumed by plant-eating reef fishes. Those fish are in turn eaten by larger carnivorous, commercially valuable finfish. The toxin, being fat soluble, is transferred and mag-



Courtesy of SeaWiFS Project, NASA Goddard, and ORBIMAGE

MYSTERIOUS BLACK WATER—In the winter of 2002, satellites and sailors observed waters in Florida Bay turning the color of black ink. Researchers speculated that the "black water" was a bloom of algae, though there were none of the typical signs of toxins or oxygen depletion and no observed die-offs of marine life. Fishermen noted that they found few fish within the region.

nified through the food chain, much as occurs with pollutants such as DDT and PCBs. That means the most dangerous fish to eat are the largest, oldest, and most desirable. Ciguatera is responsible for more human illnesses—10,000 to 50,000 cases annually—than any other kind of toxicity originating in fresh seafood.

• ***Possible Estuary-Associated Syndrome***—This vague term reflects the poor state of knowledge of the human health effects of the alga *Pfiesteria piscicida* and related organisms. Human exposure to these algae in estuaries has been linked to deficiencies in learning and memory, skin lesions, eye irritation, and acute respiratory distress. In 1997, a bloom of *Pfiesteria* caused massive fish die-offs on Maryland's eastern shore, leading consumers to avoid all seafood from the region despite assurances that no toxins had been detected in seafood products. That single event cost at least $50 million in lost seafood sales and lost recreational boat charters.

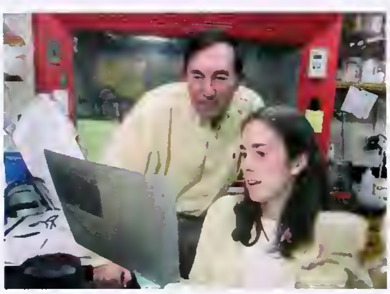
Increasing awareness

January and February 2002 — Seafarers and satellites notice something amiss in the Gulf of Mexico. The seas north and west of the Florida Keys have grown dark, with nearly 700 square miles of water (two-thirds the size of Rhode Island) taking on the color of black ink. Tests show this "black water" has normal salinity and oxygen levels, but researchers suspect an unusual, non-toxic algae bloom. There are none of the usual signs of a HAB, but fishermen note that the black water seems to be devoid of fish.

Researchers call the recent expansion of HABs an "apparent" trend because for many locations, poor historic data are available. It is not clear whether the increase in HAB reports reflects heightened scientific awareness of coastal waters and scrutiny of seafood quality, or a real increase in the number, severity, or frequency of outbreaks due to pollution and global change.

Researchers suspect that many "new" bloom species are simply "hidden flora" that had existed in those waters for many years. Such species had not been detected or recognized as harmful until scientists developed more sensitive toxin detection methods and trained more observers, or until aquaculturists placed shellfish or fish resources in areas where toxic species had been lurking.

That part of the expansion may be a result of increased awareness should not negate our concern, nor should it alter the manner in which we mobilize resources to attack it. The fact that harmful algal blooms are at least partly due to human activities makes our concerns even more urgent.



Tom Kleindinst, WHOI Graphic Services

Donald M. Anderson (reviewing data with Research Associate Deana Erdner) earned a bachelor's degree in mechanical engineering and a doctoral degree in aquatic sciences from the Civil Engineering Department of the Massachusetts Institute of Technology. He accepted a postdoctoral position at WHOI in 1978 and joined the staff as an Assistant Scientist in 1979. Anderson became interested in red tides and HABs as an MIT graduate student when a massive red tide devastated the New England coast. His work investigating chemical factors regulating *Alexandrium* blooms led to discoveries of a cyst stage and other biological processes that became his research focus. Since then, his research program has expanded and now ranges from molecular and cellular studies of toxin genetics to large-scale studies of the oceanography and ecology of algal blooms. He is actively involved in the organization and implementation of national and international programs for research and training on HABs. He serves as director of the U.S. National Office for Marine Biotoxins and Harmful Algal Blooms (based at WHOI). The National Oceanic and Atmospheric Administration named him an "Environmental Hero" in 1999. He does eat shellfish and other seafood, both at home and abroad, but is careful to learn whether the product is from approved waters. As a rule, he does not eat large, tropical reef fish. Don is an accomplished golfer, and is currently the Massachusetts Senior Amateur Champion.

A Fatal Attraction for Harmful Algae

Clay sticks to algae and sinks, offering a potential solution to an expensive and deadly problem

By Mario R. Sengco, Postdoctoral Investigator
Biology Department
Woods Hole Oceanographic Institution

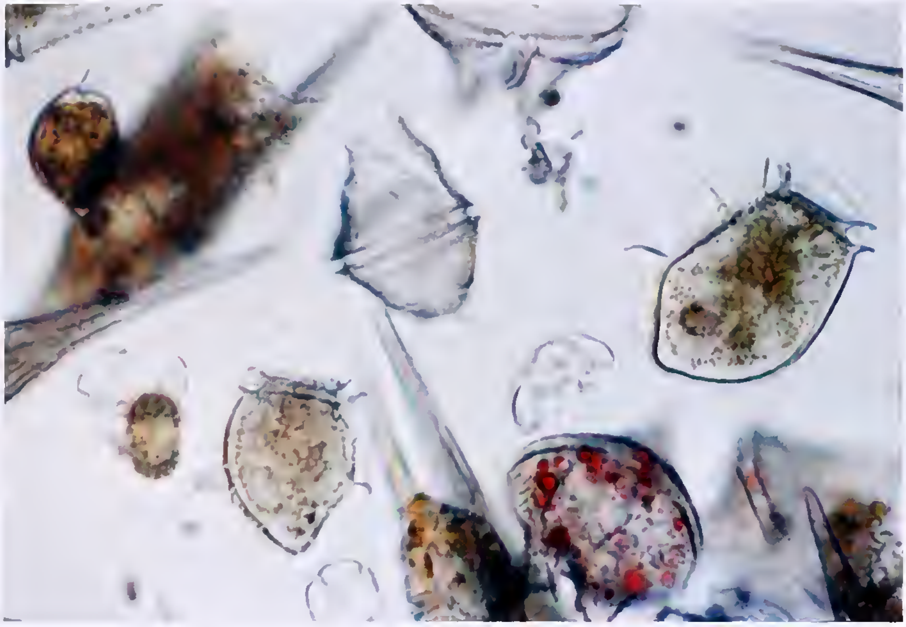
A Korean scientist once told me a folk tale about an ancient emperor who ordered servants to rid his garden ponds of an algal scum that killed his fish and blemished his kingdom. One perceptive servant noticed that whenever rain washed dirt, sand, and other sediments into the ponds, the water cleared and the fish appeared healthier. As a test, he sprinkled various sediments into the water, discovering that clay was particularly effective. The algae disappeared, and the emperor was happy.

The story offers insight into how people in Asia may have discovered that they could use clay to rid their waters of "red tide" and "brown tide." Exactly how it works is a more recent discovery.

Through laboratory and field experiments, we now know that moistened clay weighs down algal cells, causing them to sink. On the seafloor, the fallen clay crushes many of these microscopic plants. Lack of sunlight kills the rest.

Jim Cutter, Mote Marine Laboratory

CLEANING UP WITH CLAY—Scientist Mike Henry of the Mote Marine Laboratory sprays clay slurries into Florida's Sarasota Bay while WHOI Postdoctoral Investigator Mario Sengco and colleagues in the other boat track the dispersal of the plume with water sampling devices. The researchers are investigating the use of natural clays as a potential tool to mitigate harmful algal blooms, or "red tides."



Don Anderson, WHOI

LITTLE PLANT, BIG PROBLEM—Harmful algal blooms are caused by species of tiny plants—phytoplankton—that produce potent chemical toxins. Fueled by periodic abundances of nutrients in the ocean, these algae multiply and proliferate until they can cover tens to hundreds of miles of coastal ocean.

The results of this treatment can be striking. After spraying clay in Japan's Inland Sea during the late 1980s, researchers noted that blooms of harmful algae quickly declined, water clarity improved, and populations of yellowtail and opaleye fish recovered. After South Koreans began clay treatments in 1996, fishery losses fell from $100 million to $1 million per year.

In the United States, clay treatment is not yet permitted as a control strategy for algal blooms because there are questions about the ecological consequences of this sort of remediation. But as more and more coastal communities struggle with contaminated fish, undermined economies, and public health risks, interest in a solution has soared. Biologists at Woods Hole Oceanographic Institution are part of a team examining clay therapies that could someday be used to mitigate and control harmful algal blooms.

A centuries-old problem

Popularly known as "red tides" or "brown tides" because of how they discolor the water, harmful algal blooms are a natural phenomenon that has been recorded since the book of Exodus. They are caused by species of tiny, plant-like cells—phytoplankton—that produce potent chemical toxins. Fueled by periodic abundances of nutrients in the ocean, these algae proliferate until they cover tens to hundreds of miles of coastal ocean. (See "The Growing Problem of Harmful Algae," page 34.)

These blooms occur worldwide and have particularly affected fisheries in Scandinavia and Asia, reef inhabitants in the Caribbean and South Pacific, and shellfisheries along U.S. coasts. For example, harmful algal blooms caused by the species *Karenia brevis* along the Gulf Coast of Florida have caused extensive fish kills and contaminated shellfish. In humans, the toxins of this tiny plant can trigger coughing, itchy skin, and respiratory problems.

Given all the trouble linked to these toxic plants, it would seem that people would welcome any technique to stem the tide of algae. But opponents of clay treatment argue that clay threatens bottom-dwelling creatures such as clams and mussels, clogging their filters used for feeding. They also say that clay compromises water quality and too greatly interferes with a naturally occurring process. Proponents counter that the cost is small compared to the devastating impact of algal blooms on fish and the livelihoods of fishermen.

Chemicals, skimmers, and clams

In the 1950s, Florida waters became an early U.S. test bed for remedies to curtail harmful algae. Crop-dusting planes headed offshore, spraying copper sulfate over vast expanses of sea. It proved an expensive and temporary fix, knocking out the algae for just a few days while devastating

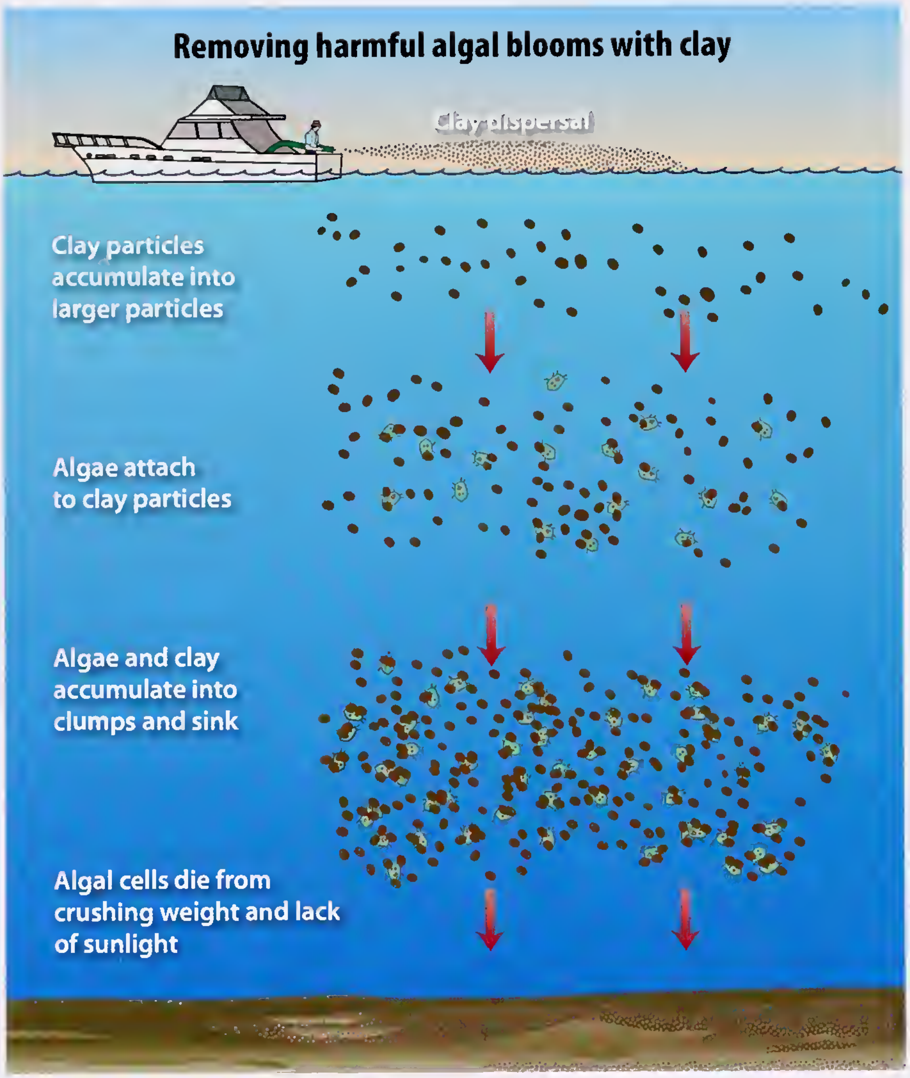
National Fisheries Research and Development Institute, South Korea

ON GUARD AGAINST ALGAE—In South Korea, fish farmers spread clay to ward off harmful algae that could devastate the crop in their pens. The results can be striking. After South Koreans began clay treatments, fishery losses fell from $100 million to $1 million per year.

the fish and shellfish population.

Coastal managers, scientists, and engineers have tried other strategies, with mixed success. Some have tried water filters, pumps, and surface skimmers, only to find that they clogged or suffered mechanical breakdowns. More recently, researchers tested algae-eating clams and mussels—even parasites. There are high-tech proposals to use ultrasonic waves or ozone gas bubbles to cause the algae to burst.

Amidst the innovation, clay appeals as a low-cost, pragmatic solution. It has been the focus of my research for seven years.



Jack Cook, WHOI Graphic Service.

A magnetic attraction

Algae stick to clay particles just as a magnet clings to a refrigerator—through the bonding of positive and negative charges on their surfaces. When clay is sprayed onto the surface of waters contaminated with harmful algae, the algal cells attach to the clay, become burdened with its heavy load, and fall to the seafloor. On the way down, the algae-clay particles collide with and gather more algae, forming masses of fluffy debris called "marine snow."

I started my graduate studies by working with colleagues to identify the best clay for making this algal snow. Not all clay is suited, as some allow algae to pass right through the falling particles without sticking. We tested about 100 types of clay.

My colleagues and I found the most effective clays had a very fine grain and were rich with the mineral montmorillonite. We identified about a dozen pure clays and a few clay-rich sediments that fit this profile. In experiments with *Karenia brevis*, the toxic algae common off Florida, we found that our clays removed up to 90 percent of the algae. We had similar successes with affected waters from Washington, Texas, and New York.

Impacts on the seafloor

The use of clay may be effective for clearing surface waters, but how does all this falling debris affect the organisms on the bottom? Clams, mussels, and other benthic creatures typically survive on the seafloor by filtering food from overlying water. So before we decide clay is the answer to our algae problems, we need to see how these bottom-dwellers react to clay exposure.

In a series of experiments with colleagues from Canada's Institute for Marine Biosciences and from Dalhousie University in Nova Scotia, we found that if we sprayed water with small amounts of clay and allowed it to settle, the clams neither died nor differed in their growth compared to untreated clams.

But when we added clay to areas where currents kept clay particles suspended in the water column for longer periods (in our test case, more than two weeks), shell and tissue growth in clams slowed by as much as 90 percent. This suggested that it was important to avoid clay application in places where particles take a long time to settle.

In another experiment at the Environmental Protection Agency's laboratory in Gulf Breeze, Fla., colleagues compared the harm caused by clay and toxic algae on grass shrimp, sheepshead minnows, and two burrowing crustaceans. In both 4-day- and 28-day experiments, clay alone was not lethal. But when combined, the mixture of clay and toxic algae proved deadly.

Since clay treatment may not be more harmful to bottom-dwelling organisms than an untreated bloom, clay could be useful to prevent the impacts of algae near the surface of the water, where many impacts on public health and fish occur.

Aishao Li

TEXAS TWO-STEP—In an experiment in Corpus Christi, Texas, WHOI scientist Mario Sengco pumped algae-rich water into tanks and treated them with clay. Within hours, the sinking clay removed more than 70 percent of the algae.

Taking clay to the real world

In the past few years, we have started testing our results in the field, taking clays and instruments to the sites of a brown-tide event (caused by *Aureococcus anophagefferens)* near Long Island, N.Y., *Karenia brevis* red tides in Florida and Texas, and a fish-killing *Heterosigma akashiwo* outbreak in Washington's Puget Sound. In most cases, we pumped algae-rich waters from coastal environments into tanks and treated them with clay; sometimes we captured a parcel of water in a natural enclosure where it could then be treated and studied. Each time, we removed more than 70 percent of algae within hours of treatment.

Each success leads us to try experiments on ever-larger scales and under more realistic conditions.

In 2003, we released 130 kilograms (287 pounds) of clay in a cove in Sarasota Bay. We tracked its movement from the surface to the seafloor to see how currents, tides, and other environmental factors would influence the movement, settling rate, and eventual distribution of clay in the sediment.

We found that much of the clay sank within 10 to 30 minutes of dispersal; within an hour, the water column had returned to its pre-treatment clarity. The distribution of clay within our study area appeared to have been determined by the direction and speed of the currents near the bottom, which we measured using current meters and other ocean instruments.

Based on this work, we are confident that we should be able to track a plume in unsheltered waters. Recently we secured permits and permission to try our techniques in the open waters of Sarasota Bay. We are curious to see what happens in a less controlled environment, where the clay and algae will be stirred by the ocean's natural ebbs, flows, currents, and turbulence.

An unexpected cleaner

People accustomed to scouring clay from baseball uniforms, tennis whites, or pottery scrubs are a little surprised when I tell them I am using clay to clear toxic algae from coastal waters. Then I remind them how we already use clay as a cleaning tool. A blob of clay rubbed on the edge of books lifts dirt away. At spas, people pay to have clay smeared on their faces to remove oils. Environmental cleanup crews use clay to absorb oil from spills.

Given the economic and environmental costs of other potential remedies for toxic algae, we have to continue to ask: Why not clay?

Tom Kleindinst, WHOI Graphic Services

For a young Filipino boy curious about the sea, Manila's outdoor market full of fresh seafood provided an ideal laboratory. After school and on weekends, Mario Sengco visited the market to examine the silvery bodies of fish and to prod their gills "just to see how they worked." After moving to New Jersey at age 14, Sengco eventually took his interest in ocean life to Long Island University, where he studied marine biology. During his sophomore year, he attended a lecture on red tides by WHOI biologist Don Anderson, who in 1996 became Sengco's graduate advisor in the MIT/WHOI Joint Program in Oceanography and Oceanographic Engineering. In 2002, he received the first Panteleyev Award, presented to a graduating student who exemplifies a commitment to improving student life and the educational experience at WHOI. "I did it through song," he jokes. A tenor, Sengco coordinated several a cappella groups on Cape Cod and appeared in musicals at MIT. He is now a postdoctoral investigator in the WHOI Biology Department.

Red Tides and Dead Zones

The coastal ocean is suffering from an overload of nutrients

By Andrew R. Solow, Senior Scientist and Director, Marine Policy Center
Woods Hole Oceanographic Institution

The most widespread, chronic environmental problem in the coastal ocean is caused by an excess of chemical nutrients. Over the past century, a wide range of human activities—the intensification of agriculture, waste disposal, coastal development, and fossil fuel use—has substantially increased the discharge of nitrogen, phosphorus, and other nutrients into the environment. These nutrients are moved by streams, rivers, groundwater, sewage outfalls, and the atmosphere toward the sea.

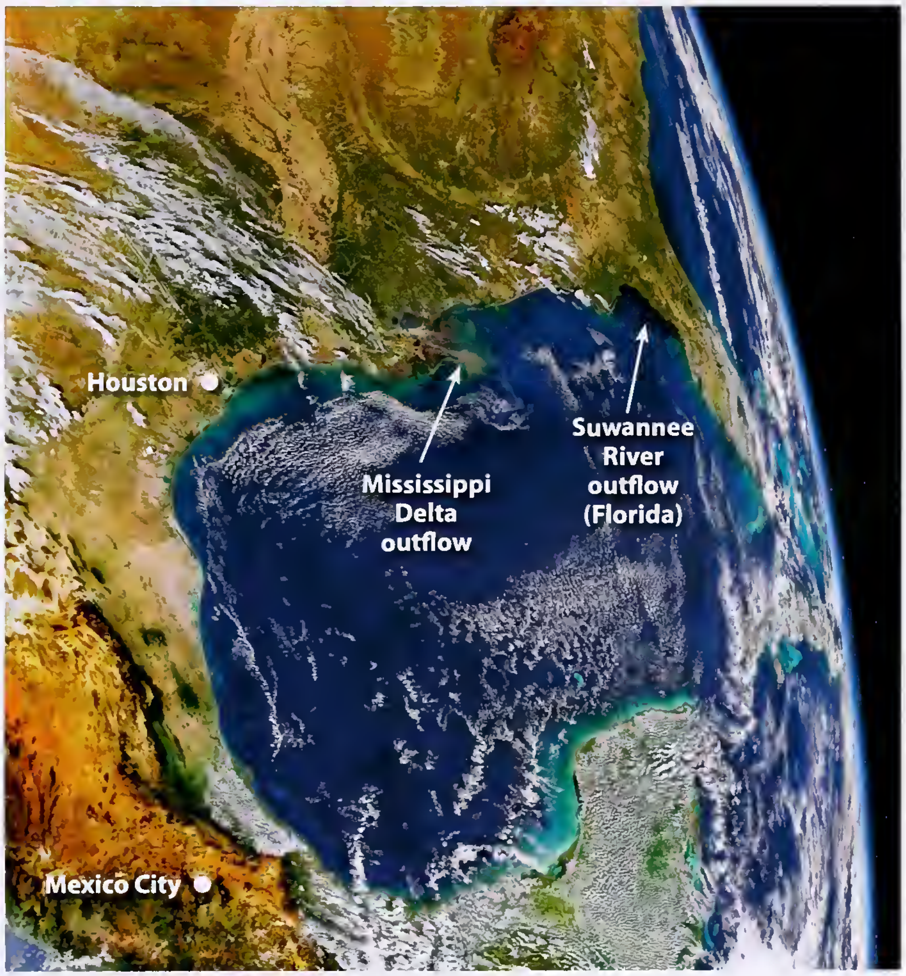
Once they reach the ocean, nutrients stimulate the growth of tiny marine plants called phytoplankton or algae. When the concentration of nutrients is too high, this growth becomes excessive, leading to a condition called eutrophication.

There is a clear connection between eutrophication and two significant environmental problems: harmful algal blooms (HABs) and the depletion of oxygen dissolved in bottom waters (hypoxia). The effects of both HABs and oxygen depletion are felt throughout the coastal ecosystem, with direct and indirect effects on human health, food supplies, and recreation.

For scientists seeking to understand it, eutrophication is a challenge because the physical and biological processes linking nutrients and their impacts are complex. For policymakers seeking to manage these impacts, the challenge is weighing the economic benefits of the activities that generate nutrients with the environmental costs of eutrophication.

Too much of a good thing

In the ocean, as on the land, photosynthesis combines energy from the Sun with carbon dioxide and nutrients such as nitrogen and phosphorus to produce carbon-rich plant material. This natural process is called primary production and forms the base of the marine food chain. It also provides most of the oxygen in the atmosphere. Without primary production, the world would be a much different (and a good deal less pleasant) place.



RIVER PLUMES ON THE GULF COAST—On Nov. 7, 2004, a satellite captured the outflow of river sediments and dissolved nutrients into the Gulf of Mexico, as well as the abundance of algae and phytoplankton in the water. Dark green or black patches near the shore indicate blooms of marine plants. White spots are clouds. Each summer, a stagnant, oxygen-depleted "dead zone" forms in the middle of the Gulf, likely caused by a surplus of nutrients from inland sources.

But every silver lining has a cloud. Of the thousands of species of algae, perhaps only a hundred are toxic. When these species occur in high concentrations, they can color the water and produce what are popularly referred to as "red tides" or "brown tides." Scientists prefer to call these outbreaks harmful algal blooms or HABs. (See "The Growing Problem of Harmful Algae," page 34.)

Toxic algae enter the marine food chain when they are consumed by small marine animals called zooplankton and by fish or shellfish. The toxins that accumulate in these consumers are then passed up the food chain to marine mammals, seabirds, and even humans, where they can cause illness or even death.

Blooms of some non-toxic species of algae can also cause problems. For example, the North Atlantic right whale is in grave risk of extinction. This species feeds seasonally off Cape Cod on concentrated patches of zooplankton called copepods. In some years, an algal species called *Phaeocystis* blooms in Cape Cod Bay. Although *Phaeocystis* is not toxic, large blooms essentially clog surface waters and right whales cannot find the copepod patches they need to eat.

Non-toxic HABs include large blooms of seaweed or macroalgae that can coat beaches, interfering with recreational activities. Other HABs clog seagrass beds and coral reefs, which provide nurseries for commercially important fish and support high levels of biological diversity necessary for a healthy environment

Harmful algal blooms occur in every part of the world. In the U.S. and other developed countries, monitoring efforts and fishery closures have reduced the incidence of human illness caused by toxic algae. However, both monitoring and closures have economic costs that can be substantial. Perhaps the most striking example of this is the complete loss of the wild shellfish resource in Alaska—which once produced 5 million pounds annually—to persistent paralytic shellfish poisoning.

It is difficult to assess the precise way in which human activities influence the occurrence and severity of HABs. The physical and biological processes involved are not well understood, and long-term observations are sorely lacking. To complicate matters, HABs can and do occur in relatively pristine conditions. But there is a clear connection between nutrient levels and primary production, and there is general agreement among scientists that, other factors being equal, the conditions that favor high levels of primary production also favor HABs.

Is it getting stuffy in here?

Phytoplankton can cause problems even when they are dead. After they die, phytoplankton sink to the bottom where they decay through bacterial action. The bacteria that cause decay use oxygen dissolved in bottom waters. As long as the bottom waters are well mixed with oxygen-rich surface waters, the oxygen is renewed. However, under certain conditions, ocean waters become stratified so that there is little vertical mixing, and depleted oxygen is not replaced.

Stratification tends to occur in the summer because the configuration of warm surface waters over colder bottom waters is stable. Stratification also tends to be stronger near the mouths of rivers where the lighter fresh water overlays denser salt water in a stable configuration. (See "Where the Rivers Meet the Sea," page 22.) Finally, stratification is strong in enclosed and semi-enclosed parts of the ocean—such as bays and lagoons—that are cut off from the large-scale circulation patterns that promote mixing.

When vertical mixing is weak or absent, oxygen-depleted bottom waters are not refreshed, resulting in a condition called hypoxia. Hypoxic areas—popularly known as "dead zones"—can have a dramatic effect on marine life. In some cases, oxygen depletion occurs so quickly that it cuts off escape routes and results in fish kills.

Overabundance of nutrients can cause certain marine plants to grow like weeds, choking off food sources for fish and shellfish, or literally asphyxiating the creatures from lack of oxygen.

Even when animals simply avoid low-oxygen areas, as they usually do, the indirect effects of hypoxia can be substantial. Suitable habitat is lost, putting pressure on populations. Hypoxic zones also can interfere with the migratory behavior of shrimp, lobsters, and other species. More generally, by altering the environment in which marine species thrive, hypoxia can lead to a decline in biological diversity.

A widespread problem

Hypoxia occurs throughout the world. Two of the best-known hypoxic areas are in the Black Sea and the Baltic Sea. In the U.S., dead zones occur regularly in

Long Island Sound, the Chesapeake Bay, and the northern Gulf of Mexico. In the Baltic Sea, hypoxia has contributed to the collapse of the Norwegian lobster fishery. There is evidence that the hypoxia off the coast of Louisiana has harmed the valuable shrimp fishery and possibly contributed to the replacement of bottom-dwelling species such as snapper with less valuable mid-water species such as menhaden.

Hypoxia can occur naturally. For example, the bottom waters of the Black Sea have been depleted of oxygen for thousands of years. Hypoxia has also occurred naturally in the Chesapeake and the Gulf of Mexico. But there is little doubt that, by increasing the level of nutrients in the ocean, human activities have increased the frequency, extent, and severity in these areas and throughout the coastal ocean.

Digital Vision

NEXT STOP, COASTAL WATERS—Pesticides and fertilizers sprayed far from the coast still find their way to the ocean, running off farmlands into rivers, streams, and groundwater. Minor changes in agricultural practices could save money for farmers and reduce nutrient pollution in the sea.

Decisions we can live with

Determining the appropriate public policy response to eutrophication is difficult. Because so many economic activities contribute nutrients to the marine environment, nutrient regulations potentially touch a large part of the economy. Also, the effects of eutrophication are complicated and difficult to measure, especially in economic terms. Comparing the costs and benefits of alternative policies is difficult. While eutrophication is ubiquitous, different regions differ in both cause and effect. For this reason, policy must be customized to local situations: One size does not fit all.

The good news is that, because so many human activities produce nutrients, there are many opportunities to make small, low-cost changes with a large cumulative impact.

One promising approach to nutrient reduction involves the adoption of so-called "best management practices" in agriculture. A major contributor to nutrient pollution is the loss of fertilizer from agricultural fields. Not only does this ultimately lead to eutrophication, but it is also costly to farmers. By using improved agricultural methods such as no-till planting, farmers can put more fertilizer in the soil and less in the ocean.

Another area for possible action is improving the treatment and disposal of human and animal waste. Although this is likely to be costly, it has benefits beyond the reduction of eutrophication.

Finally, policies could also be aimed at curtailing the conversion—and even promoting the restoration—of wetlands and other natural buffers that intercept and sequester nutrients before they reach the ocean.

Aquaculture for remediation?

There are some novel ideas as well. A project is currently underway at Woods Hole Oceanographic Institution to examine the feasibility of using shellfish aquaculture to reduce nutrients in the coastal ocean. The experimental shore-based aquaculture system at the National Center for Mariculture in Eilat, Israel, uses shellfish to absorb excess nutrients excreted by fish. Researchers at WHOI are trying to determine whether the same idea is feasible in the ocean. As the shellfish produced by such an enterprise have economic value, this is an example of a win-win situation. (See "Down on the Farm Raising Fish," page 66.)

As environmental problems go, coastal eutrophication is not particularly glamorous. It is difficult to justify costly measures to eliminate this problem, particularly in the short term. But low-cost options do exist and would be a step in the right direction. Not only would this make economic sense today, but it would set us on a course to lighten the tread of society on natural systems.

— *This article is adapted from "Red Tides and Dead Zones: Eutrophication in the Marine Environment," which first appeared in* U.S. Policy and the Global Environment.

Tom Kleindinst, WHOI Graphic Services

Andrew Solow is Director of the Marine Policy Center and a Senior Scientist at Woods Hole Oceanographic Institution. He earned a bachelor's degree in economics from Harvard University and a doctorate in geostatistics from Stanford University. Solow focuses on environmental and ecological statistics, with an emphasis on modeling the population effects of environmental variability. He is a former member of the Commission on Geosciences, Environment, and Resources for the National Academy of Sciences, and he currently serves as chair of the Environmental Protection Agency's Outfall Monitoring Science Advisory Panel for Boston Harbor. Since 2002, he has been a member of the Science Advisory Panel for the U.S. Commission on Ocean Policy.

Mixing Oil and Water

Tracking the sources and impacts of oil pollution in the marine environment

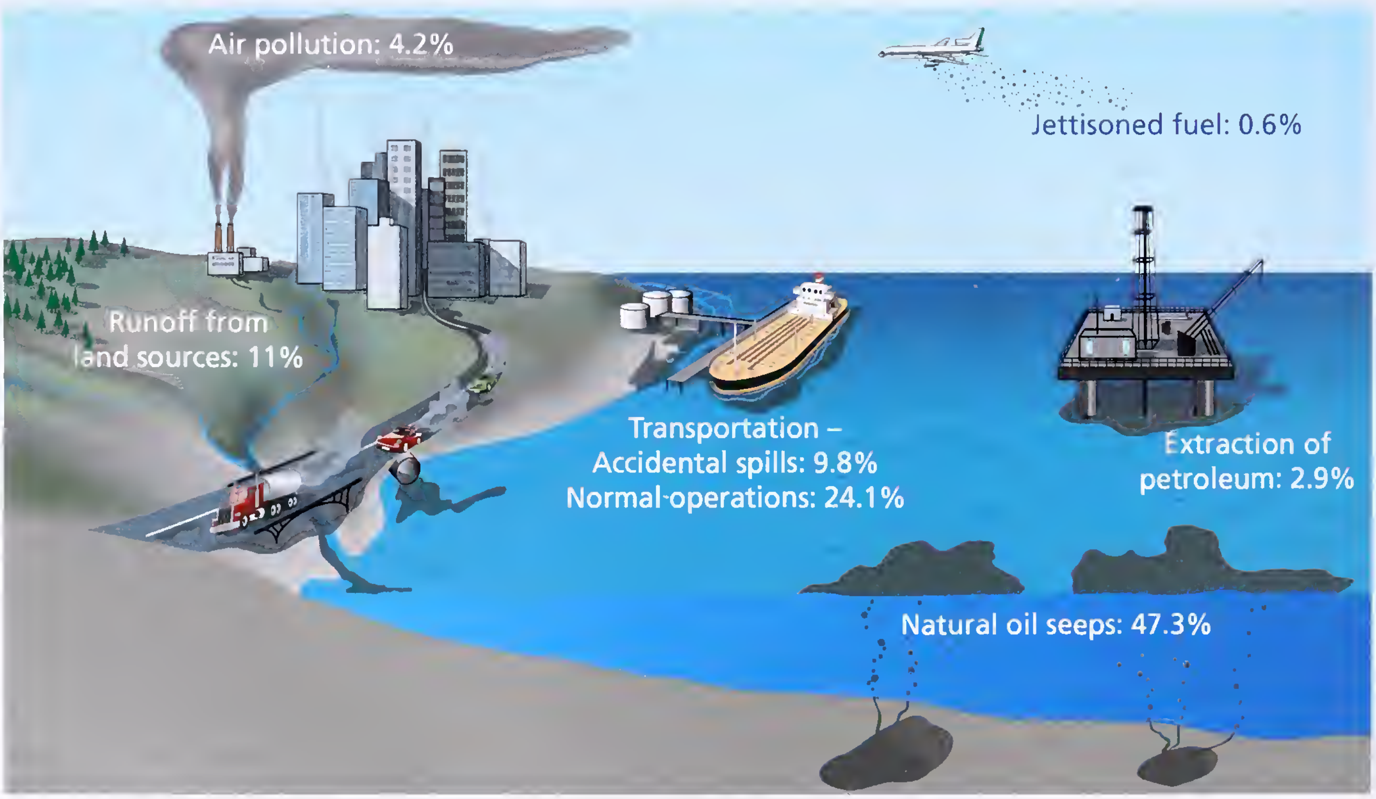
By John W. Farrington, Senior Scientist
Vice President and Dean of Academic Programs
and Judith E. McDowell, Senior Scientist
Biology Department
Associate Dean of Academic Programs
Woods Hole Oceanographic Institution

Drop by drop—that is how most oil enters the oceans. Catastrophic spills make the headlines, but it is the chronic dribble, dribble, dribble of seemingly small inputs that supplies most of the oil pollution in the world's oceans.

In recent decades scientists have made substantial progress in understanding how oil enters the oceans, what happens to it, and how it affects marine organisms and ecosystems. This knowledge has led to regulations, practices, and decisions that have helped us reduce sources of pollution, prevent and respond to spills, clean up contaminated environments, wisely dredge harbors, and locate new petroleum handling facilities.

But tracking the sources, fates, and effects of oil in the marine environment remains a challenge for a number of reasons. For starters, oil is a complicated mixture of hundreds, sometimes thousands, of chemicals. Every source of oil, and even the same general types of oil (crude oils or fuel oils, for example) can have distinctive compositions depending on which oil field or well they came out of and how they were refined.

This varying, complex mixture of chemicals gets spilled or seeps into an

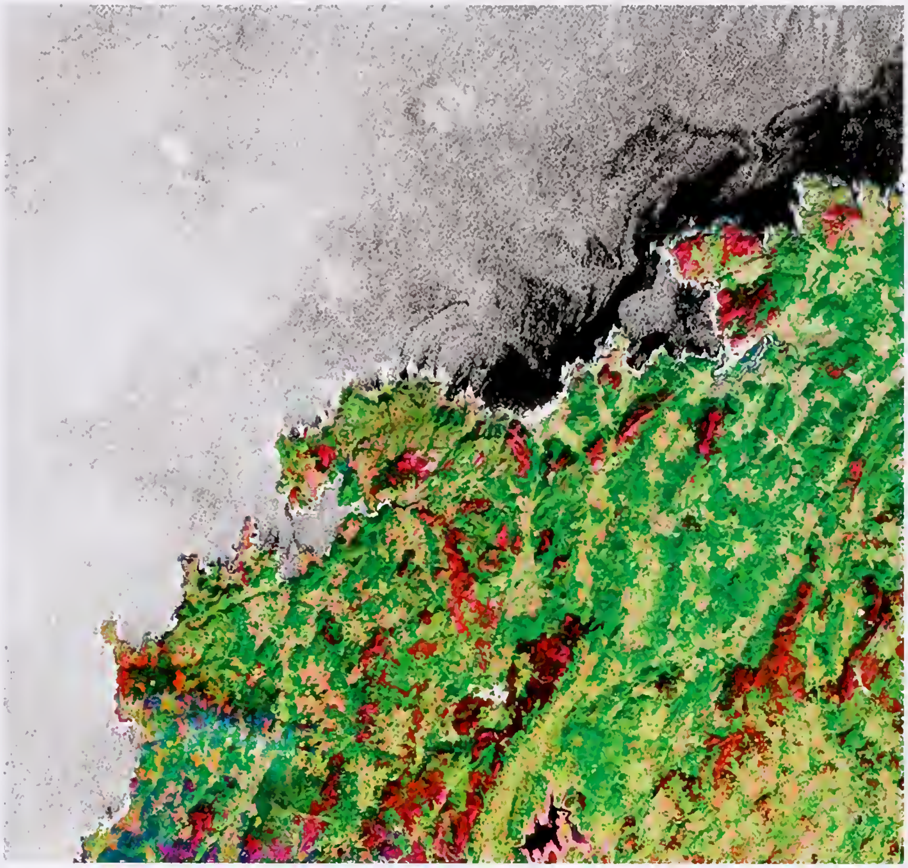


Jack Cook, WHOI Graphic Services

HOW DOES OIL GET INTO THE OCEAN?—About 380 million gallons of oil enter the world's oceans and coastal waterways each year from natural and human sources. This illustration shows the approximate worldwide percentages arriving from each source; the relative inputs of oil can vary significantly in different parts of the world. The percentages for transportation include oil lost specifically in oil/petroleum commerce (tankers, pipelines, etc.), as well as the normal operation of all other sea-going vessels.

already complex chemical chowder of seawater, mud, and marine organisms in the ocean. There, the oil is stirred by currents, tides, and waves, altered by other physical processes, and changed further by chemical reactions and interactions with organisms in the sea.

In the midst of this dynamic situation, scientists seek to pinpoint the impacts of oil on myriad individual species, as well as on entire ecosystems. Here the challenge comes full circle, because we now know that the impact of oil can vary greatly, depending on its distinctive chemical composition. But let's start at the beginning.



RADARSAT / Canadian Space Agency

A 30-MILE SLICK—Satellite rador images show the extent of the 2002 Prestige *oil spill olong the northwest coast of Spain. The slick (block oreos) is visible because oil smooths the ocean surface. Clean water appears bright because it scotters ond reflects light back toward the sotellite. Oil can have wildly different impacts depending on the location of the spill ond the weother conditions in the hours ond days afterward.*

How does oil get into the ocean?

Scientists have known since the 1970s that accidents account for only a small percentage of the oil entering our waters. In fact, accidental spills of all types—from ships, shore facilities, pipelines, and offshore platforms—contributed just 9.8 percent of the oil entering the marine environment on an annual, worldwide basis between 1990 and 1999 (but just 3 to 4 percent in U.S. waters).

That doesn't mean we should dismiss the importance of spills. Accidents such as the 1989 *Valdez* incident off Alaska or the 2002 *Prestige* spill off Spain can have devastating effects on marine life and on people's ability to use the ocean. The impact of a spill depends on the type of oil, the amount spilled, the ocean and weather conditions, and the dynamics of the area or ecosystem where it takes place.

Progress in prevention—through more stringent laws, rules, and guidelines, and increased vigilance by industry and regulators—has reduced accidental spills, at least in developed countries. For instance, studies of tanker spills have prompted regulations for the steady, ongoing replacement of single-hulled tankers in the world fleet with double-hulled tankers.

But spills are just one small way, albeit dramatic, for oil to mix with our waters. So where is the rest of it coming from?

• **Seeps:** Between one-third and one-half of the oil in the ocean comes from naturally occurring seeps. These are seafloor springs where oil and natural gas leak and rise buoyantly from oil-laden, sub-seafloor sediments that have been lifted close to Earth's surface by natural processes.

If oil is natural to the oceans and if it is the biggest source of input, what is the fuss about oil as a pollutant? The answer lies in the locations and rates of oil inputs. Oil seeps are generally old, sometimes ancient, so the marine plants and animals in these ecosystems have had hundreds to thousands of years to adjust and acclimate to exposure to petroleum chemicals. On the other hand, the production, transportation, and consumption of oil by humans often results in the addition of oil to environments and ecosystems that have not experienced significant direct inputs and have not become acclimated.

• **Extraction:** Accidental and normal operation of oil drilling and production platforms puts some oil into the sea, including oil mixed into the briny waters that escape from the oil reservoirs. But this spillage and waste, and the atmospheric releases from platform equipment, is one of the smallest sources of oil in the sea.

• **Transportation:** In the 1960s and 1970s, scientists studied tar balls collected along major tanker routes and the beaches downstream. They revealed that large amounts of oil were entering the marine environment as a result of ballast water (bilge) discharges and other aspects of "normal" tanker operations. As a result of that research, international conventions and national laws and regulations have led oil shippers to minimize their discharges, particularly in harbors. Today, in spite of

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WORSE THAN AN OIL SPILL—The everyday "normal" activities of industrialized society—driving, shipping, heating buildings, operating industrial machinery—put far more oil and its byproducts into the oceans than all major spills combined. The impact of oil from petroleum-fueled vehicles might even be understated, since the chronic drip of oil from millions of cars and trucks is extremely hard to measure.

increasing numbers of tankers plying the seas, the amount of oil spewed has stabilized or decreased in many places.

• **Consumption:** The everyday use of oil in cars, trucks, industrial and manufacturing plants, and other machinery of the modern economy is the most egregious and insidious source of oil pollution. The drippings and emissions from millions of machines accumulate on land and eventually run into our waterways.

From the 1950s through the 1970s, one of the most common sources was the indiscriminate disposal of used automobile crankcase oil down sewer systems. Since that time, scientific findings have prompted regulations and public awareness campaigns that promote the recycling and proper disposal of used oil.

But we still have a problem. Peer underneath your parked car and observe the drip of oil. This happens day and night for millions of automobiles, trucks, and buses, creating a chronic, significant source of oil to the sea. Rainstorms wash these drippings into streams or storm sewers that discharge into harbors and rivers. It is terribly hard to measure these types of inputs.

Fossil fuel hydrocarbons from engine exhaust also accumulate in the atmosphere. Sometimes the soot is deposited into our waters; otherwise it is washed out of the atmosphere and into the oceans by rain or snow.

On a smaller scale, new research has shown that outboard engines of small boats and pleasure craft are a significant source of oil pollution—up to 2.2 percent of all inputs in U.S. waters (worldwide data are not available). Engine manufacturers are responding with new models of engines that release much less oil and gasoline, but it may take some time for these changes to propagate through the boating community.

What happens to oil in the ocean?

Oil chemicals entering the ocean have many fates. Volatile chemicals are lost by evaporation to the atmosphere. Other chemicals are broken up by photochemical reactions (catalyzed by sunlight). Bacteria can degrade certain oil components.

The combination of biological, physical, and chemical processes is usually referred to as weathering. These weathering reactions have different rates depending on the chemical structure of the oil, habitat conditions (such as water temperature or oxygen and nutrient supply), and mixing of the water by wind, waves, and currents. In some spills, oil does not last much beyond weeks to months.

But when oil pours into shallow waters with muddy sediments—such as marshes or lagoons—and conditions allow the oil to become mixed into the mud, it will generally persist for a long time. This is a result of the fundamental chemistry of oil compounds. Since they don't dissolve in water, oil compounds tend to adhere to particles in the water or get incorporated into biological debris, such as fecal matter or dead organisms. These oiled particles and debris settle from the water column and become part of the sediments on the bottom.

Once mired in the sediment, some oil chemicals can persist for years or decades, depending on the environment. In areas swept by high-energy currents, the material may be dispersed. In areas where sediments accumulate (such as ship channels through urban harbors), the contaminated sediments become an environmental concern—both when simply lying on the bottom and when channels are dredged and the mud must be disposed.

For some types of oil inputs and some ecosystems, we now have enough information to model and simulate the fate of oil in the water. This scientific knowledge helps policymakers make better decisions on how to dredge harbors, control pollution sources, clean up contaminated areas, and locate petroleum facilities.

How does oil affect marine life?

From experiments and field measurements, we know that certain types and concentrations of petroleum chemicals can harm marine life. Long-term effects of oil exposure can alter the physiology and ecology of populations of marine organisms, especially those found in sensitive habitats.

Biological and physical processes can reduce the concentration of oil chemicals in an ecosystem, especially if the source of pollution is cut off. As concentrations decline and chemical compositions change, plant and animal communities usually rebound. But the recovery can range from months to decades depending on the chemistry, the conditions, and the organisms and ecosystems affected.

One of the significant advances in the 1970s and 1980s was the development of guides to the sensitivity of various types of coastal ecosystems to oil pollution. Maps of sensitive ecosystems are now used during responses to accidental oil spills, improving the ability of resource managers and engineers to assess where containment booms and other prevention and cleanup measures should be deployed.

There have been few studies, however, on the cumulative effect of chronic inputs of oil to the marine environment, including the many sources associated with oil consumption on land. Assessing these impacts is complicated because oil runoff is often accompanied by other polluting chemicals, making it difficult to tease out which ones have which deleterious effects. Limited experiments have taught us that the interactive effects among chemicals can either increase or decrease each chemical's long-term effects, depending on the organisms and chemicals.

Much of our knowledge about the effects of oil is still limited. It has focused on biochemical and physiological effects on a few individual organisms and on the degradation of a few particular habitats. But we need a better understanding of the large-scale effects of oil on entire communities and populations, rather than individual organisms. The complexity of how species interact within ecosystems—such as how damage to one species can affect the other species that feed on it—leads to contentious debate whenever regulators start to weigh long-term impacts on marine life.

Fuel for further research

A high priority for the future should be better monitoring and research so we can better quantify how much oil is really entering our waters, how much of it is coming from each source, and what the effects may be.

We also need to expand research on oil pollution in deeper waters. Most concerns and research have traditionally focused on coastal waters. Yet new concerns arise as oil production moves offshore. We can only speculate on the impact of oil exploration and production in deeper waters until we have more detailed knowledge of the biological organisms in these habitats and the biogeochemical processes that govern their lives.

Developed countries and emerging countries consume more oil every year, and that consumption leads to more and more inputs of oil to the oceans. We have learned from our colleagues in developing countries that increased use of fossil fuels has not been accompanied by the sort of stringent regulations developed countries adopted after years of harsh lessons. Further research and education can help those countries minimize the adverse impacts of oil inputs on their oceanic ecosystems.

—*A recent study by the U.S. National Academy of Sciences, entitled* Oil in the Sea III: Inputs, Fates and Effects, *provided the foundation for this article.*

John Farrington came to WHOI in 1971 as a postdoctoral investigator in the Chemistry Department following completion of bachelor's and master's degrees at Southeastern Massachusetts University and a doctorate at the University of Rhode Island. His research interests include marine organic geochemistry, biogeochemistry of organic chemicals of environmental concern, and the interaction between science and policy. He has served on scientific advisory panels for the National Academy of Sciences, the National Science Foundation, the Office of Naval Research, and the Commonwealth of Massachusetts.

Judith McDowell earned her bachelor's degree in biology from Stonehill College and her master's and doctorate degrees in zoology from the University of New Hampshire. Judy's research focuses on the ecology of marine animals and the effects of chemical contaminants on the marine environment. She has served on the Committee on Oil in the Sea for the National Research Council. She is director of the Woods Hole Sea Grant Program.

Oil in Our Coastal Back Yard

Spills on WHOI's shores set the stage for advances in mitigating and remediating oil spills

By Christopher M. Reddy, Associate Scientist
Marine Chemistry and Geochemistry Department
Woods Hole Oceanographic Institution

On September 16, 1969, the barge *Florida* ran aground off Cape Cod, rupturing its hull and spilling 189,000 gallons of No. 2 fuel oil. Winds and waves pushed the oil onto the beaches and marshes of West Falmouth, Massachusetts, carrying with it dead lobsters, scup, and cod.

In the weeks and months after the spill, biologists Howard Sanders and George Hampson from the nearby Woods Hole Oceanographic Institution (WHOI) collected samples of mud and animals from the marsh sediments, particularly from an area known as Wild Harbor. They shared their samples with Max Blumer and Jerry Sass, WHOI geochemists who knew how to analyze oil with one of the field's newest tools, the gas chromatograph.

Together, they made a discovery that refuted the prevailing wisdom of the day: Oil lurked in the marsh and sub-tidal sediments long after it was no longer visible in the water and on the beaches.

Three decades later, my research group returned to those marshes. Equipped with our own state-of-the-art equipment—a two-dimensional gas chromatograph—we analyzed new sediment samples and made our own discovery. Some of the oil from the *Florida* spill is still buried in the mud, and its chemical composition has not changed dramatically since the mid-1970s.

The *Florida* oil spill is perhaps the longest studied in history, and it has fundamentally changed our understanding of what happens to oil in coastal ecosystems. We are still building on this groundbreaking research, seeking knowledge that

Kevin Mingora, Cape Cod Times

LEARNING FROM DISASTER— Chris Reddy, a marine chemist at Woods Hole Oceanographic Institution, examines and collects oil-covered rocks at Nyes Neck in West Falmouth, Mass., following the April 2003 spill from the Bouchard 120 *oil barge. Reddy and colleagues study the impact of oil and other contaminants on coastal ecosystems, with a particular eye on how the compounds disperse and decay.*

could help mitigate the environmental impact of future oil spills and the costs of cleaning them up.

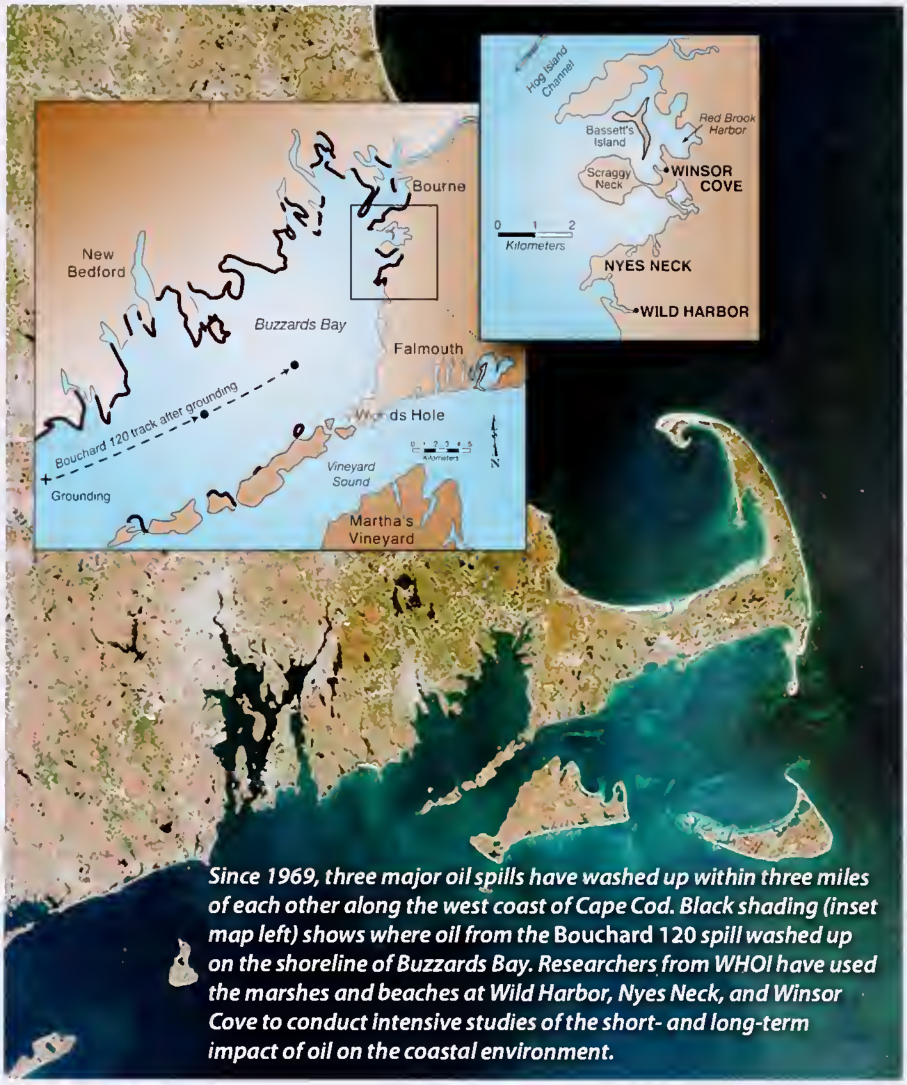
Oil spills are awful for the environment, but they provide an excellent opportunity to study how the ocean and its ecosystems respond to extreme events. (See "Mixing Oil and Water," page 46.) Most people see a spill and focus only on its toxic effects. But my group also sees it as a huge injection of carbon-based food for microbes in the coastal environment. We ask questions like: How long does it take the oil to decay and be consumed by microbes? How long will oil persist at a particular location and why? Do people need to intervene and assist in cleanups, or can Mother Nature remediate the ecosystem herself?

A history of spills and research

New England relies heavily on barges for transporting fuel to its major ports and cities. For decades, Buzzards Bay has been a major thruway for oil barges, with approximately 2.1 billion gallons of oil traveling through the Cape Cod Canal each year. With so many barges navigating these rocky and narrow waterways, spills due to mechanical or human errors are almost inevitable.

In September 1969, the inevitable happened. When the barge *Florida* ran aground, it released the largest amount of oil spilled in Buzzards Bay history. "The oil-soaked beaches were littered with dead or dying fish," wrote Hampson and Sanders in *Oceanus* at the time. "Fish, crabs, and other invertebrates covered the shores of the Wild Harbor River and large masses of marine worms, forced from their natural habitat in the sediments, lay exposed and decaying in the tidal pools."

Applying the most advanced analytical techniques of his day, Blumer was able to study the chemical composition of the oil from the spill. Oil products such as No. 2 fuel oil are made up of hundreds of individual chemicals that vary in their characteristics, such as volatility, solubility, and toxicity. Blumer was able for the



Since 1969, three major oil spills have washed up within three miles of each other along the west coast of Cape Cod. Black shading (inset map left) shows where oil from the Bouchard 120 *spill washed up on the shoreline of Buzzards Bay. Researchers from WHOI have used the marshes and beaches at Wild Harbor, Nyes Neck, and Winsor Cove to conduct intensive studies of the short- and long-term impact of oil on the coastal environment.*

Photo NASA, Maps: Jack Cook, WHOI Graphic Services

Table 1: Known Oil Spills in Buzzards Bay, MA

Date	*Location*	*Type*	*Volume (gallons)*	*Comments*
1940s	Western 8uzzards Bay, Westport (at Hen and Chicks)	No. 2 fuel oil	unknown	
1963	Near Nyes Neck, North Falmouth	No. 2 fuel oil	unknown	Came ashore during the winter.
9/16/1969	Fassets Point,West Falmouth	No. 2 fuel oil	189,000	*Florido* fuel barge. Final estimate was 4,500 barrels spilled.
10/9/1974	Cleveland Ledge (near canal entrance)	No. 2 fuel oil	11,000 to 37,000 (under review)	*Bouchord 65* barge grounded. Towed to an anchorage off Wings Neck. Oil came ashore in N. Falmouth and 8ourne.
1/28/1977	Cleveland Ledge	No. 2 fuel oil	81,144	*Bouchord 65* barge grounded, oil on iced-over bay, some burned. Final estimate was 1,932 barrels spilled.
6/10/1990	Cleveland Ledge	No. 6 fuel oil	7,500	*Bermudo Stor* cruise ship went aground, impacts to Naushon.
6/18/1990	Cleveland Ledge	Diesel or heating oil	100 or 200	*Bouchord 145* fuel barge
8/7/1992	Sow and Pigs Reef, Cuttyhunk	No. 6 fuel oil	50	*Queen Elizobeth II* cruise ship. Residual from empty fuel tank that was ruptured.
4/27/2003	Press reports: Hen and Chicks Reef, Westport	No. 6 fuel oil	98,000 (not final)	*Bouchord 120* fuel barge
Smaller spills of gasoline and fuel oil have occurred every few years in the bay or in the Cape Cod Canal.				

Dr. Joseph Costa, Buzzards Bay Project

LASTING IMPACT—The Bouchard 65 *spill of 1974 devastated the marsh of Winsor Cove in West Falmouth, Mass. Though the* Spartina *(marsh grass) was not visibly coated with oil after the spill (left), enough chemical compounds settled into the underlying peat and sediments to wipe out the vegetation for years afterward (right photo, 1977). Thirty years later, WHOI biologist George Hampson still monitors the marsh grasses, which have not recovered to their pre-1974 state. New work reveals that petroleum hydrocarbons still persist in the marsh.*

first time to tease out which compounds had evaporated and decayed and which remained in Wild Harbor. He saw some of the oil's constituent parts, rather than one uniform chemical.

WHOI salt marsh ecologist John Teal and graduate student Kathy Burns also studied Wild Harbor through the mid-1970s, and Teal and chemist John Farrington revisited the old spill in 1989. Each time, remnants of the 1969 oil persisted.

Several other oil spills have occurred in Buzzards Bay since the *Florida* spill (see page 51). In October 1974, thousands of gallons of No. 2 fuel oil from the barge *Bouchard 65* poured into the bay, with the greatest impact in Winsor Cove, just two miles north of Wild Harbor. Building on their experience, WHOI researchers measured and chronicled the 1974 spill for comparison with the 1969 event, as both involved the same type of fuel and neighboring but somewhat different shorelines. We have found that oil at Winsor Cove from the *Bouchard 65* spill also continues to persist.

The amount of oil spilled in each case has been rather small compared to some high-profile spills like the Exxon *Valdez*. But the convergence of these spills, all occurring within 10 miles of Woods Hole, has created a unique natural laboratory for investigations of the short- and long-term fates of oil in the coastal ocean.

Who does the better cleanup job?

The Oil Pollution Act of 1990 requires that parties responsible for an oil spill must attempt to restore the environment to its pre-spill condition. One popular approach is "natural attenuation," allowing or promoting natural processes to clean up and remove contaminants from affected areas.

Environmental scientists presume that, over time, naturally occurring or artificially transplanted microbes will eat hydrocarbons in the petroleum soup. It is an attractive, feel-good alternative when compared with labor-intensive and costly cleanup schemes, and several studies have shown that natural attenuation can sometimes be as effective as human intervention.

In the first days and weeks after a spill, physical processes churn the oil around in the water, exposing it to air and sunlight, causing some compounds to evaporate or be broken up. Then the "bugs" take over.

Oil spills can deliver a staggering amount of carbon—that is, food for the ecosystem—in a short period of time. A rough calculation from the *Florida* spill indicates that 50 to 100 grams of carbon were added to each square meter of the impacted area in one day. By comparison, natural photosynthesis by plants yields about 300 grams of carbon per square meter in an entire year.

Petroleum hydrocarbons provide a rich source of high-caloric food for a variety of microbes. In many ways, these microbes match or exceed humans in their chemical skills, using an incredible toolbox of enzymes to break down complex petroleum compounds. But just how do these microbes break down the oil? And why haven't they eaten all of the oil from the 1969 spill?

Back to the future

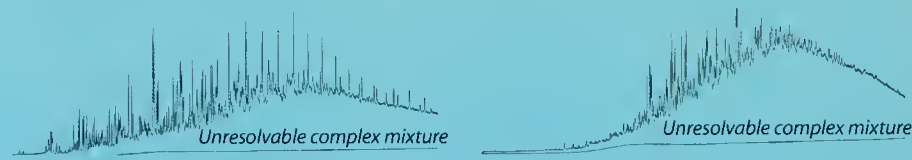
Answering these questions requires that we learn a lot more about the chemistry and composition of oil and its natural degradation processes. We started by going back to the site of our predecessors' work in the salt marshes of Wild Harbor and Winsor Cove.

We collected dozens of sediment cores, particularly from a site in Wild Harbor that was named M-1 (marsh sample 1) by previous WHOI scientists. Like Blumer a generation ago, we brought a powerful scientific tool to bear on the problem. With colleagues Glenn Frysinger and Richard Gaines of the U.S. Coast Guard Academy, we analyzed our sediment samples using a novel technique called comprehensive two-dimensional gas chromatography (GC×GC) in order to observe how the composition of the 30-year old oil had changed while buried in the marsh. It was the first time anyone had used GC×GC to

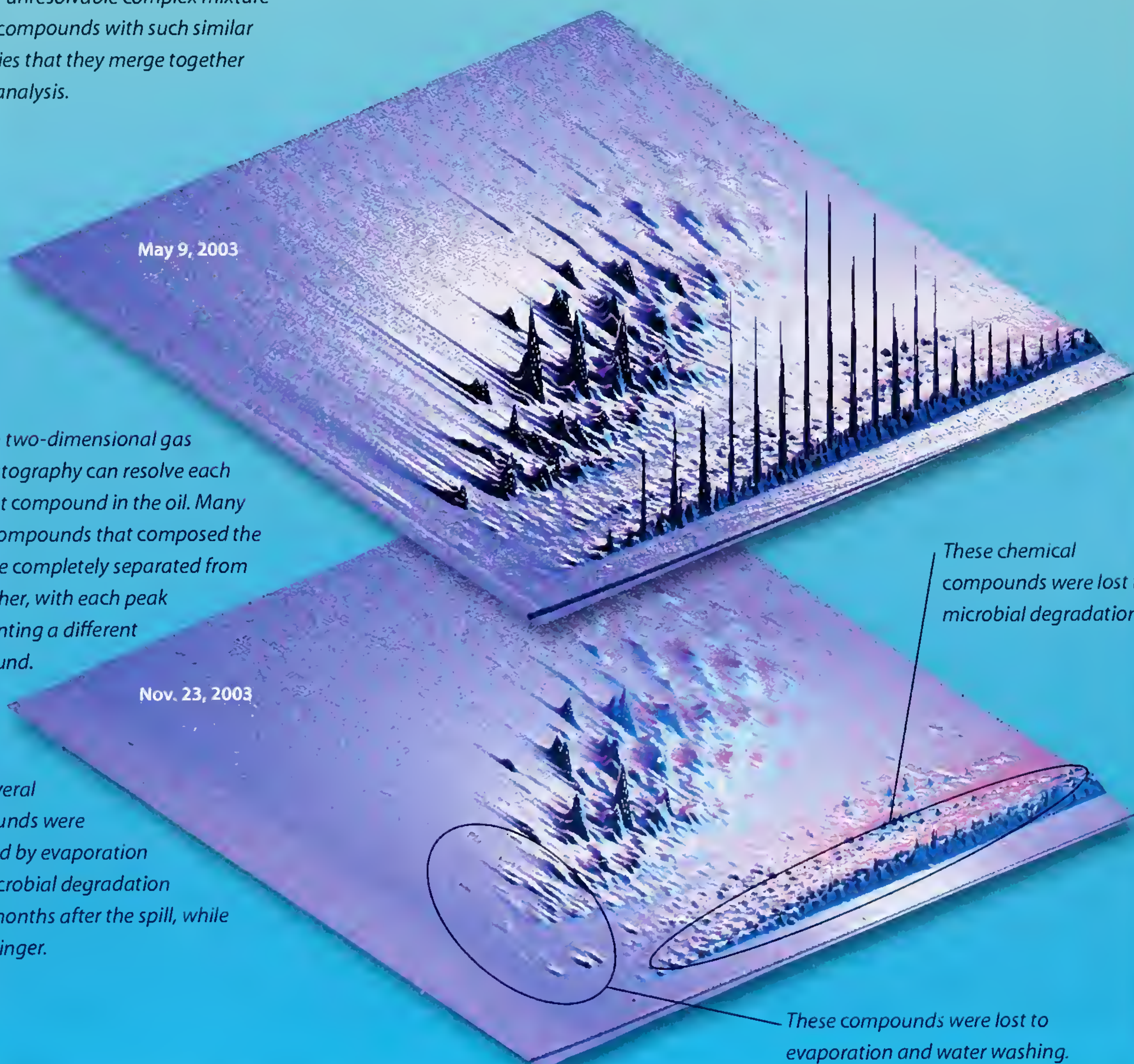
Seeing the needles in the haystack

The analysis of oil compounds has come a long way in three decades, as changes in analytical equipment and in computer handling of data have allowed researchers to better delineate the type and proportion of oil compounds present in different samples. The data below show traditional gas chromatography and the cutting-edge view for oil-covered samples collected at Nyes Neck two weeks and six months after the *Bouchard 120* oil spill.

Traditional gas chromatographs (right) can delineate some of the chemical constituents in an oil sample, but cannot resolve the details, particularly the proportion of one compound versus another. Note the hump that chemists call the "unresolvable complex mixture" (UCM), compounds with such similar properties that they merge together during analysis.



Modern two-dimensional gas chromatography can resolve each different compound in the oil. Many of the compounds that composed the UCM are completely separated from each other, with each peak representing a different compound. These results reveal that several compounds were removed by evaporation and microbial degradation in the months after the spill, while others linger.



Robert K. Nelson, WH

analyze a real-world oil spill.

With traditional one-dimensional gas chromatography (GC, as used by Blumer's generation of environmental chemists), scientists could identify about 10 percent of the compounds in the oil, a quantum leap for the era. But that process still leaves a haystack of many compounds (such as branched alkanes, cycloalkanes, and aromatics) that cannot be identified. On a data plot, it looks like a large hump that we call the unresolvable complex mixture (UCM). Too many of the compounds have similar properties and when analyzed with a simple chromatograph, they merge together, making it impossible to tell one from another.

With modern GC×GC, we can find needles in that haystack (see page 53). We have been able to separate and identify many more compounds and provide a more refined inventory of the petroleum hydrocarbons that persist in the marsh.

We found that the oil at the M-1 site had not weathered significantly since the mid-1970s, and most of the compounds typically found in oil are still present after three decades. As we peered into the previously unresolved mass, for instance, we found that certain types of alkanes remain, despite earlier research that suggested they were completely degraded.

The oil for food program

I doubt many people would have predicted in 1969 that oil from the *Florida* spill would still be present after three decades. The entire marsh continues to be mildly affected, and there are certain areas along the shoreline where oil is particularly concentrated. Why doesn't the oil go away?

Our findings from Wild Harbor and Winsor Cove suggest that some marsh sediments might be ideal for preserving partially weathered petroleum. Evidence indicates that oil-consuming bacteria may have stopped eating these hydrocarbons more than 25 years ago. Though a diverse community of microbes exists in the contaminated regions of Wild Harbor, they are not actively consuming the remaining oil.

We have started numerous experiments to figure out this riddle, and knowing what types of chemicals remain can provide essential clues. The contaminated sediments may now lack oxygen required by some microbes to degrade hydrocarbons rapidly. Perhaps the environment is missing a key chemical species—such as sulfate—that bacteria need to consume and change the remaining oil compounds.

Perhaps the chemical bonds and structures of certain oil compounds locked the microbes out, resisting their chemical attacks. Or maybe the microbes prefer to eat

Photos by Kevin Mingola / Cape Cod Times

NOT SO SLICK—At least 98,000 gallons of fuel oil were spilled into the waters west of Cape Cod, Mass., in April 2003 after the barge Bouchard 120 *(inset) struck an underwater ledge. The accident prompted legislators in Massachusetts to increase fines for oil spills, implement new safety standards and navigational rules, and impose a two-cent-per-barrel fee to establish a fund for oil spill response and training.*

more readily available food sources such as plant debris.

A new spill to investigate

On April 27, 2003—just six months after we published our findings on the 1969 oil residues in Wild Harbor—the barge *Bouchard 120* struck an underwater ledge while being tugged to a power plant. At least 98,000 gallons of No. 6 fuel oil poured into Buzzards Bay, and within 24 hours, helicopter surveys showed a 12-mile oil slick. Viscous, tarry petroleum washed up on the beaches of one of New England's richest tourist and shellfishing grounds.

Like our WHOI predecessors, Research Associate Bob Nelson and I went to the beaches to collect samples and observe firsthand the war between industrialized society and Mother Nature. We scooped floating "pancakes" of petroleum, filled bottles with oily blue water, and collected tarred cobbles and sediments.

After a year of analyzing samples, we have been able to determine the original chemical composition of the *Bouchard 120* oil and track how it has changed. Our early results show that several groups of compounds were lost to evaporation, water washing, and microbial degradation (see page 53). The degradation of oil, however, seems to have stalled after the initial breakup in the first six months. Because the responsible party removed nearly all of the oil-impacted rocks at this site, we can no longer collect samples there.

Howard Sanders, WHOI

TWO GENERATIONS—For 30 years WHOI researchers have chronicled the effects of oil spills on the west coast of Cape Cod, Mass. Above, from left: George Hampson, Linda Morse Porteous, and Arnie Carr discuss the effects of the 1974 Bouchard 65 *spill on Winsor Cove. Below, from top: Bob Nelson and Chris Reddy collect water samples and oil "pancakes" from Buzzards Bay in April 2003.*

C. A. Linder, WHOI

Treasures in the attic

Coastal oil spills are incredibly destructive, with intense short-term consequences and insidious long-term ones. No one wants to witness an oil spill, but they happen. And when they do, we need to take advantage of the opportunity to learn from them.

WHOI is an extraordinary place to do that, thanks to three decades of samples and memories in these labs. As recently as June 2004, Bruce Tripp, a long-time member of the research staff and participant in the earlier oil spill studies, handed me a dusty jar he had recently found in a storeroom. It was a sample of oil collected by WHOI scientists in 1974 from the *Bouchard 65* spill, which will be invaluable for our continued work on coastal spills.

The National Science Foundation, the Petroleum Research Fund, the Environmental Protection Agency, the Office of Naval Research, and the WHOI Coastal Ocean Institute provided funding for this research.

—WHOI Science Writer Mike Carlowicz and Research Associate Robert Nelson contributed to this article.

Christopher Reddy studies the fate of contaminants in the marine environment. He grew up on Rhode Island's Narragansett Bay, and has always lived within a few miles of a coast. Chris came to WHOI in 1997 as a postdoctoral scholar after completing undergraduate work in chemistry at Rhode Island College and a doctorate in chemical oceanography at the University of Rhode Island.

Which Way Will the Wind Blow?

Marine scientists have a key role to play in the debate over wind farms in the coastal ocean

By Porter Hoagland, Research Specialist
Marine Policy Center
Woods Hole Oceanographic Institution

Two centuries ago, citizens of the new American republic relied on the winds along their shores as an economic engine. Salt farms and gristmills dotted the coastline, their windmills tapping the sea breezes for energy.

Two centuries later, Americans are looking to tap coastal winds again to fuel the modern economy, to reduce air pollution, and to mitigate global warming. Wind energy is the fastest-growing sector of the global electric power industry, and several companies have proposed to build large wind turbines and utility-scale electric power-generating facilities in the coastal waters of the United States.

Such facilities could change the way people use the ocean, and the public is divided over the costs and benefits. The environmental and economic benefits of renewable, nonpolluting sources of energy are clear. But there may be side effects from the placement of modern wind farms in the ocean, including the degradation of seascapes, impacts on birds and marine animals, and the disruption of existing patterns of human use of the ocean. The laws and regulations related to the placement of wind turbines in the ocean are at best rudimentary and inchoate; at worst, they are non-existent.

Marine scientists and engineers can make an important contribution to this growing public debate by clarifying our understanding of the nature of these side effects. They might also inform public policies that balance the value of various ocean resources with the rights and interests of all who wish to use them.

A NEW FARM CROP—Situated 8 to 12 miles off the west coast of Denmark, the Horns Rev wind farm is the world's largest. The 80 turbines are spread across 7.7 square miles, with blades stretching 360 feet into the air. Completed in 2003, the project added 160 megawatts (MW) of power-generating capacity to the country's electrical grid, and it is expected to produce nearly 2 percent of the nation's electric power. European nations have plans to add nearly 5,000 MW of wind power production in the coming years, and nearly 50 wind farms have been proposed for U.S. waters.


Courtesy of William Quinn. Engraving by J.W. Barber and S. E. Brown

SEEING THE FUTURE IN THE PAST—An engraving from the 1840s shows the coastline of Provincetown, Mass., dotted with wind-powered salt mills. The artist noted: "The numerous wind or salt mills, and the elevations of sand, give the place a novel appearance."

Major Freeman's legacy

Just after the American Revolution, Major Nathaniel Freeman of Harwich, Massachusetts, suggested using wind energy to pump seawater into large vats onshore, where it could evaporate to form salt crystals. As chronicled by historian William Quinn, salt was crucial for preserving fish and furs both for American consumers and European markets. Spurred by government incentives and federal tariffs on imports, 1,260 "salt mills" sprouted along the coast of Cape Cod by the 1830s.

During their heyday, coastal salt works were so lucrative that they were referred to as a "lazy man's gold mine." The bottom fell out of the business in the mid-19th century, when it became cheaper to harvest salt from the more saline springs of Virginia, Kentucky, and upstate New York.

At least 39 wind-powered gristmills were built on Cape Cod in those early years as well. Operated by "dry-land sailors," the gristmills provided energy for industry and incidentally served as important navigational landmarks. The advent of steam power meant the end of the gristmills, though some were relocated to the properties of affluent landowners who admired their beauty and sound construction.

Ironically, many coastal property owners now oppose building modern windmills. This opposition is one measure of how Cape Cod and other coastal areas have shifted their economic bases from farming and natural resource exploitation to tourism and recreation.

Winds of change

In the past decade, worldwide electricity production from wind has grown by 30 percent. Several factors have rejuvenated interest in wind power. Technological advances in turbine and blade designs over the past 20 years have reduced the cost of producing electricity with wind by as much as 80 percent. At the same time, governments have responded to the growing public interest in technologies that reduce pollution and mitigate the impact of global warming caused by carbon dioxide emissions from the burning of fossil fuels.

Government policies also have encouraged this development. At the U.S. federal level, a tax credit subsidizes the production of electricity from wind power at the rate of 1.6 cents per kilowatt hour (kWh). Generating facilities powered by wind are also eligible for accelerated capital depreciation, making it easier to recoup some of the expenses of building wind farms.

Many states have begun to adopt policies requiring utility companies to supply a proportion of power from renewable sources, including wind, hydropower, and biomass. In addition, many states have adopted tax breaks that parallel the federal subsidies. Some have developed research and development programs for renewable energy, financed by so-called "public benefit charges" on consumer electricity bills.

With subsidies and the economies of scale that can be achieved with large turbines, wind power can now be produced in some areas of the United States for as little as 3 cents per kWh, making it competitive with other energy sources. Land-based, utility-scale wind turbines now operate in 26 states. The U.S. accounts for roughly 16 percent of the world's wind power generating capacity. Although U.S. capacity is now nearly 6,400 megawatts (MW), wind power supplies less than one percent of current U.S. energy needs.

Courtesy of William Quinn

TALES OF WIND AND WATER—The Judah Baker gristmill (center) and a salt mill (left) stood near the coast of South Yarmouth, Mass., in 1866 at the height of a boom in "dry-land sailing." The wind powered nearly 1,300 salt- and gristmills along the shores of Cape Cod in the 19th century. The Baker gristmill has since been moved inland and serves as a tourist attraction.

New proposals on the horizon

Utilities in Europe have been generating power from ocean wind for more than a decade, ever since the Vindeby facility off Denmark became operational in 1991. Wind farms are being developed off the coasts of Denmark, Great Britain, Sweden, and the Netherlands, creating 246 MW of power generating capacity—including 160 MW at the Horns Rev wind farm that came online in 2003 along Denmark's west coast. An additional 5,000 MW of capacity is planned for northern Europe.

In recent years, proposals have been floated—some serious and some ridiculous—for as many as 50 wind farms in the U.S. coastal ocean and Great Lakes. The ocean attracts wind energy companies because winds tend to be stronger and more consistent over open areas, such as large bodies of water. Also, the "land" for placing turbines is cheap because the ocean is a public resource and not privately owned.

There is little precedence for modern wind farming in the United States, so there are no provisions for renting areas of the ocean to wind farmers, as there are for oil and natural gas producers. The lack of a precedent leads to contradictions. For instance, is it sensible for the government to subsidize wind power on one hand while charging a "land rent" on the other?

There are also serious questions about which agencies, federal and local, have the authority to make decisions about this resource. The existing federal permitting process for regulating offshore wind farms is loosely based on the Rivers and Harbors Act of 1899, which gives jurisdiction to the U.S. Army Corps of Engineers over any "obstructions to navigation." While navigational issues for ships are important, the issues surrounding wind farming go well beyond navigation. Neither the old law nor the more recently developed public review process appears adequate for making decisions about the use of the ocean for activities such as wind farming.

Running aground on the shoals

These vagaries and gaps have spawned an impassioned debate and a public policy quandary. Since 2002, the center of that debate has been Nantucket Shoals, off the southeast coast of Cape Cod.

Successful small-scale wind power projects on Cuttyhunk, Nantucket, and other islands in the 1970s and 1980s inspired interest in placing large wind turbines and a utility-scale power facility in the coastal waters of New England. The current proposal includes 130 wind turbines—each 400 feet tall—to be located 0.3 to 0.5 miles apart within a 25-square mile area of Nantucket Sound.

Public opposition to wind farms in nearshore waters is based mainly on worries that they will spoil seascapes and have detrimental effects on birds, marine animals, and their habitats. Other groups have expressed concerns about the potential impact on sailors and important commercial fisheries.

Cape Cod and the islands of Nantucket and Martha's Vineyard are national tourist havens. Many summer homes have outstanding views of the nearby sounds, where the sailing is superb, the stripers and blues run thick, and fishing for lobster, scallops, and squid has been a popular livelihood for ages. If the wind farm is built on Nantucket Shoals, these views, and quite possibly the established pattern of ocean activities, could be altered permanently. Consequently, many Cape Codders and Islanders who otherwise support the idea of renewable energy—just not on Nantucket Shoals—have become opponents to the wind farmers.

Need for coastal ocean research

Why not put wind farms far out in the ocean, beyond the sight of land, where winds are even stronger? After all, if wind farms are developed in more remote sites, the potential for public opposition should dwindle significantly and the wind resource would grow. (In fact, civil engineering professor William Heronemus of the University of Massachusetts suggested in

1972 that it was feasible to construct an array of floating "wind stations" as far offshore as Georges Bank.)

As with most environmental problems, this potential solution entails tradeoffs. Wind energy developers would prefer to place wind turbines in shallow, protected waters that are close to existing electrical transmission lines. These criteria limit the number of good locations for ocean wind farms. Business models suggest that deep-water sites are less profitable, but the true costs and benefits of building wind farms in deep water are not yet understood.

Given the uncertainties surrounding wind energy as a new use of the ocean, a number of research questions have emerged. What are the effects of the ocean environment on wind turbines placed in the ocean? What are the effects of wind turbines on the ecosystem? And what are the features of a public policy that could make the tradeoffs easier to understand, leading to more rational and balanced decisions about human uses?

Marine scientists and policy experts are in a good position to help clarify and resolve these issues, and research is needed in several key areas:

Elsam A/S

Recent advances in the design of wind turbines, as well as government incentives, have made the cost of wind power production comparable to other forms of energy. But calculating their true power-generating impact is tricky. Wind farms often cite total capacity, but average production is typically 70 percent lower because winds do not always blow at optimal strength.

U.S. Electric Energy Generation by Source (2003)

Type	Generation (billion kWh/yr)	Generation (% of Total)	Cost (¢/kWh)
Coal	1,928	51	<1-6
Nuclear	781	21	<1-15
Natural gas	648	17	2-6
Hydropower	296	8	1-6
Biomass	34	1	7-10
Oil	31	1	1-3
Wind	17	<1	3-6
Geothermal	14	<1	2-8
Solar	1	<1	25-30
TOTAL	3,750	100	

Sources: U.S. Department of Energy, California Energy Commission

• Ocean physics—What is the nature of wind and wave patterns and current flows (particularly during extreme storm events) around each proposed wind farm site? How does the seafloor change over time, as a consequence of both flowing currents and seismic events? What is the likelihood of ice formation and movement through a wind farm area?

• Environmental impact—How would wind turbines affect songbirds that migrate through these regions or seabirds that frequent them as productive habitat? How do these structures affect marine ecological processes or important commercial fisheries? What is the impact of turbine noise on protected species, including whales, dolphins, and seals?

• Marine policy—How do we design a system of access that balances the needs of ocean wind developers against the legal interests of people and businesses already benefiting from these areas? What can we learn from the existing models of planning for use of the ocean and public lands?

All of these research efforts must be undertaken with an awareness of the economics of ocean wind power because the answers to these questions will affect the engineering design of offshore structures.

Prospects

Some environmentalists believe that the production of energy from both ocean- and land-based wind farms has the potential to satisfy the global demand not only for electricity, but also for all forms of energy. Realizing such a vision would require many thousands of large wind turbines, as well as the development of technologies to store the energy (such as the production of hydrogen as a fuel). It would also require a process for locating wind turbines in the coastal ocean that balances the benefits with the costs.

When faced with a new activity that might change the way we use the ocean environment, the public is often ambivalent. Today we are faced with a split between those who favor renewable energy through offshore wind farms and those who decry the potential degradation of the seascape. As new information is discovered and learning occurs, societal preferences about the mix of appropriate uses of the coastal ocean undoubtedly will shift. At the same time, science may uncover new options and opportunities, perhaps revealing the true potential for wind farms in the coastal ocean.

Dave Gray, WHOI

Porter Hoagland is a research specialist in the Marine Policy Center of Woods Hole Oceanographic Institution. He holds a bachelor's degree in biology from Hobart College, a master's in public administration from Harvard University, and master's and doctorate degrees in marine policy from the University of Delaware.

For the Navy, the Coast Isn't Clear

Oceanographers mobilize to help the Navy operate effectively in complex, shallow waters

By Rear ADM (Ret.) Richard F. Pittenger
Vice President for Marine Operations (Ret.)
Woods Hole Oceanographic Institution

Every so often, circumstances can conspire to make a battleship turn on a dime. Fifteen years ago, two geopolitical events prompted the U.S. Navy to abruptly change long-standing research priorities and steer rapidly in a new direction.

When the Berlin Wall collapsed in 1989, so did the Navy's Cold War necessity to counter the Soviet Union's huge submarine force throughout the world's deep oceans. A year later, the first Persian Gulf War shifted the Navy's interests to landing troops and operating ships in shallow, often mined, coastal waters. The research focus changed from "blue water" to what the Navy dubbed "littoral" warfare.

Oceanography for national defense

One of the strengths of the U.S. Navy has been its ability to exploit the ocean environment in the same way land-based soldiers use the landscape to their advantage. The key is understanding the ocean's physical and geological properties, a basic research endeavor promoted and funded by the Navy for six decades.

Columbus O'Donnell Iselin, second director of the Woods Hole Oceanographic Institution, was quick to realize the potential symbiosis between oceanographers and the Navy. In August 1940, he wrote a letter to Frank B. Jewett, a member of the newly created National Defense Research

WHOI Archives

A LIFE-SAVING LECTURE—During World War II, WHOI scientist Dean Bumpus teaches a class of Navy submariners how to use bathythermographs to avoid detection by enemy sonar. The instruments, developed at WHOI, measure ocean salinity and temperature, which affect the propagation of sound under water.

Committee, whose charge was to marshal the nation's scientific resources for an inevitable global war.

"The Woods Hole Oceanographic Institution…has been engaged in oceanographic research since 1931," Iselin wrote. "This memorandum sets forth some suggestions as to how the personnel and equipment of this laboratory can be better utilized for the national defense, for it seems likely that the training and experience of oceanographers will enable them to attack successfully various problems having a naval consequence."

Thus began WHOI's long and continuing tradition of research for the Navy. During World War II, Institution scientists investigated many aspects of underwater explosives. They found ways to prevent fouling of ships' hulls by barnacles, seaweed, and other marine life that caused turbulence and increased fuel consumption—research that lowered the Navy's fuel bill by 10 percent. They showed how salinity and temperature changes in the ocean affected the propagation of sound under water. They built instruments (bathythermographs) to measure these changes and trained sailors to use them to avoid detection from sonar, which "saved many of our ships," the Navy reported.

Such wartime research successes led in 1946 to the creation of the U.S. Office of Naval Research (ONR), which funds instrument and technology development and wide-ranging basic research on ocean properties and processes, particularly in ocean acoustics.

Listening for submarines

As in World War II, oceanographic research proved valuable to the Navy during the Cold War. Research begun at WHOI by Maurice Ewing and J. Lamar Worzel culminated in the discovery of the SOund Fixing And Range (SOFAR) channel, a layer of water in the ocean that acts like a pipeline for efficiently transmitting low-frequency sound over vast distances.

The discovery enabled the creation of the Navy's highly successful SOund SUrveillance System (SOSUS), which could detect submarines by their faint acoustic signals. SOSUS, and more advanced systems derived from it, allowed U.S. forces to track and, if circumstances warranted, engage Soviet submarines.

Countering the Soviet submarine threat was a daunting task, prompting a Navy research investment of about $14 billion per year, but it was a primary Cold War mission. Being able to accurately keep track of Soviet submarines whenever they operated created a powerful deterrent to a shooting war.

A new theater of operations

The end of the Cold War brought a shift in priorities and a major reduction in Navy research funding. But new conflicts emerged, as well as renewed attention to old ones in the Middle East, Yugoslavia, Korea, and Taiwan. These served to refocus the Navy's attention on learning how to operate safely and effectively in coastal waters, which are extraordinarily challenging for naval warfare.

The properties of the waters from the continental shelf to the coast are fundamentally different from the cold, deep ocean. The simple, stable, and predictable structure of water masses in the deep ocean (such as the SOFAR channel) does not exist in the shallows.

Coastal waters contain water masses with widely different temperatures and salinity levels, and the properties of these water masses are constantly affected by a wide variety of coastal factors and processes—including tides, wind-driven currents, inflows from rivers, changing air temperatures, and mixing between water masses. As the water masses shift, so does the structure of the ocean's water column and the transmission of sound through it.

The result is a highly complex and dynamic—and highly unpredictable—structure inimical to the Navy's cold, deepwater acoustic tools and techniques. Shipping noise, fishing activities, and shallow, reverberating seafloor topography add further acoustical complications.

These acoustic difficulties in coastal waters make it hard to detect mines. During the first Persian Gulf War, Iraqis used World War I-era mines deployed from small boats to staunch the movement of U.S. amphibious forces.

Another uniquely coastal danger is bioluminescence. Nutrient-rich coastal waters are full of marine life that glows when excited by movement and can reveal the presence of ships, subs, or Navy SEALs.

As they have since the days before Pearl Harbor, WHOI scientists have mobilized to conduct basic oceanographic research funded by the Navy in this new theater of operations. The four articles that follow highlight some of their work related to littoral warfare.

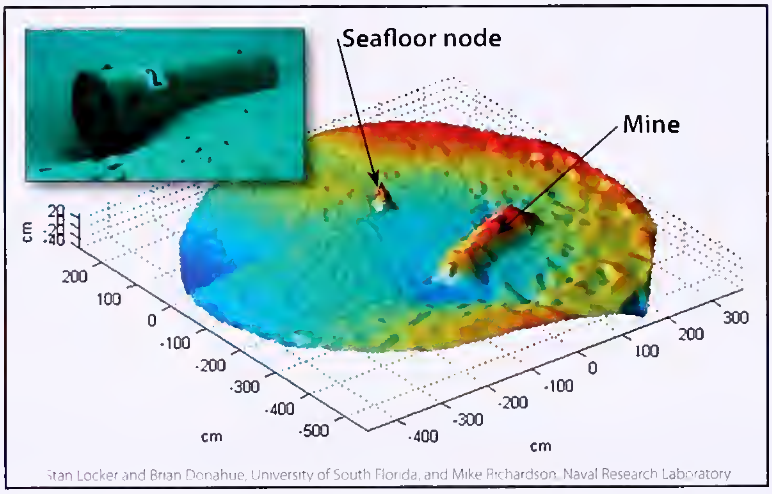
Dave Gray, WHOI Graphic Services

Dick Pittenger was born in Nebraska during the worst of the Dust Bowl/Depression era of the mid-1930s. His family moved west, eventually settling in Tacoma, Wash. Pittenger was attracted to the sea and actively participated in the Sea Scouts and Sea Cadets. He joined the U.S. Naval Reserves during the Korean War and earned an appointment to the Naval Academy through the Reserves. Graduating in 1958, Dick was commissioned an ensign and went on to serve for 32 years, rising to the rank of rear admiral. He earned a master's degree in physics (underwater acoustics) at the Naval Postgraduate School. His duties included mostly destroyers, and he specialized in anti-submarine warfare (ASW). He commanded a minesweeper in Vietnam, a fast frigate that was a member of the then-revolutionary "ASW Squadron," and a destroyer squadron. His last duties in the Navy were as director of ASW for the Chief of Naval Operations, and as the Oceanographer of the Navy. Upon retirement, Pittenger came to WHOI where he led the Institution's Marine Operations Division. His era at WHOI saw the addition of *Atlantis* to the WHOI fleet, the retirement of *Atlantis II*, the mid-life conversions of *Knorr* and *Oceanus*, the construction of the coastal research vessel *Tioga*, the revitalization of deep submergence, including bringing the tethered vehicles *Argo/Medea/Jason/DSL-120* into the National Deep Submergence Facility and, in 2004, the award of a grant to build a replacement for *Alvin*.

Where Are Mines Hiding on the Seafloor?

New research reveals how waves, currents, and swirling sands can bury mines

Eternally and incessantly, waves and currents stir up sand from the seafloor near the coast. Sediments get suspended in the ocean, carried onshore and off, and deposited elsewhere. In the process, objects on the seafloor—natural and unnatural—can get buried and uncovered.



Stan Locker and Brian Donahue, University of South Florida, and Mike Richardson, Naval Research Laboratory

MINE EYES HAVE SEEN—WHOI scientist Peter Traykovski helped reveal how mines are buried by sand on the seafloor, using a rotary sidescan sonar that continuously monitored the process. This sonar image shows a partially buried mine and the seafloor node that supplies power to the sonar.

It is a seemingly esoteric process, but the Navy has a vested interest because its enemies use mines to defend coastlines. Those mines often become buried by sand, making them all the more dangerous. Buried mines are difficult to detect, yet they still can be triggered by ships passing overhead. To assess the threats from mines and ways to avoid them—from mine hunting and sweeping to avoiding areas entirely—the Navy would like to predict what may be buried under the harbors and beaches where it wants to maneuver.

That requires an understanding of how mines get buried in different environments. In the past, divers tried to observe the processes firsthand. But diving once or twice a day, they could rarely observe a burial in progress. They merely observed the before-and-after conditions. And divers cannot work in storms and strong tidal currents—precisely the forces that cause most burials.

Observing the entire process

For more than a decade, WHOI scientist Peter Traykovski has doggedly explored the complex factors that move sand to continually reshape the seabed and our shorelines. That work has drawn attention from the Navy. Traykovski, with the assistance of WHOI scientist Jim Irish, has developed instrument systems that measure waves and currents and that capture images of sands shifting on the seafloor and suspended in the ocean.

From 2001 to 2004, Traykovski and colleagues at WHOI and the Naval Research Laboratory conducted a series of experiments, funded by the Office of Naval Research, to make continuous, long-term observations that no human divers could ever make. Using the WHOI Martha's Vineyard Coastal Observatory, they plugged instruments—including acoustic Doppler velocimeters, pressure sensors, and rotary sidescan sonars—into seafloor nodes, powered via cables from the observatory's shore-based facility. (See "The New Wave of Coastal Ocean Observing," page 16.)

In the fall, they deployed mines on the coastal seafloor, armed not with explosives but with instruments that recorded how the mines pitched, rolled, or sank. Divers who returned in April found a smooth seafloor desert and no hint of the buried mines. But Traykovski's rotary sidescan sonar—sampling every half-hour for nearly eight months and producing thousands of images—provided an unprecedented view of the processes that buried the mines.

Different sands, different effects

It turned out that mines behaved differently depending on the type of sand they sat on. In fine sand, mines jutting upward created turbulence that accelerated the flow around them. A similar process occurs when waves rush past your foot on the beach. The sand disappears around your foot, your foot sinks, and then sand washes back to fill in the hole and bury your foot. Likewise, fine sand quickly covers mines, and once buried, they stay buried.

In coarse sand, however, waves and currents create big sand ripples on the seafloor. The currents rotate the mines to align with the ripples. At that point, the mines become integrated into the rippled seascape, and currents bury them no deeper than the height of the surrounding ripples.

Armed with such information, the Navy can better predict and detect the presence of buried mines in different locales and circumstances. Beyond this crucial military relevance, Traykovski's research also offers coastal managers greater understanding of the forces and phenomena that shape our beaches, harbors, and coastal zones.

—*Lonny Lippsett*

New Instrument Sheds Light on Bioluminescence

A WHOI engineer invents a device to measure a critical but elusive ocean phenomenon

On a 1995 research cruise in the Arabian Sea, WHOI Research Engineer Paul Fucile asked an innocent question, just to satisfy his curiosity. He had been watching a three-person Naval Research Laboratory (NRL) team use a deck-mounted winch and a steel wire to maneuver a half-ton, golf-cart-sized, $500,000 piece of equipment called the High Intake Defined EXcitation (HIDEX) photometer. It was monsoon season, the weather was rough, and the crew struggled to lower HIDEX safely over the side.

"What do you measure with that?" Fucile asked, not thinking that his query would launch him into a completely new line of research.

The answer was "light"—light created by living things.

Marine organisms ranging from bacteria to fish make their own chemically induced light—called bioluminescence—to hunt, frighten predators, attract mates, communicate, or camouflage themselves. Movement in the water excites marine life to glow. It also stimulates the Navy's interest.

Bioluminescence has betrayed the positions of submarines and sealed their doom. Sailors have detected the luminous wakes of torpedoes. Returning pilots have followed luminescent trails over many miles to find their aircraft carriers, as have their enemies. Navy SEALs are mindful of certain beaches where bioluminescence would give them away.

Building a better light-trap

Bioluminescence is ubiquitous in the oceans, and especially prevalent in coastal regions where nutrients are abundant and life thrives. Yet scientists have little basic understanding of how bioluminescence is influenced by water temperatures, depths, seasons, geographic locations, even different times of day. They have been limited by a scarcity of observations and instruments to make them.

After watching his colleagues' difficulties with HIDEX, Fucile spent his night watch that evening drawing a sketch for a light-sensing instrument that was smaller, sturdier, less complicated, and less expensive. From the ship, he e-mailed a list of materials to WHOI Experimental Machinist Mark St. Pierre, asking him to get them ready so that Fucile could start construction as soon as he returned.


Tom Kleindinst, WHOI Graphic Services

WHOI engineer Paul Fucile invented an inexpensive, easy-to-deploy bathy-photometer. It measures light levels from bioluminescent marine life, which can reveal the positions of Navy ships, subs, and SEALs.

Eight weeks later, back in the Arabian Sea with the same NRL team, Fucile tested a prototype of his bathy-photometer, an instrument to measure bioluminescence in the ocean. The NRL team was impressed with the initial results. It worked well enough to earn Fucile a Cecil H. and Ida M. Green Technology Innovation Award, given to WHOI engineers to launch new ideas in instrumentation or technology. A year later, he was awarded an Office of Naval Research grant.

Portable, tough, and inexpensive

Fucile's patented 10-pound, 28-inch-long instrument is so inexpensive, it's expendable. His Expendable Bathy-Photometers (XBPMs) can be easily transported and pitched over the side of a ship by one person even in the worst weather conditions. As they descend, the XBPMs spool out a thread-like wire that transmits digital data to a computer on deck. Fucile also developed and patented this telemetry system.

The sophisticated HIDEX is capable of making a wide range of subtle measurements, including distinguishing individual types of bioluminescent plankton. But for the first-order task of measuring bioluminescence levels, the XBPM is about 90 percent as accurate as HIDEX—without HIDEX's fragile and expensive glass-tube technology. Thus, Fucile envisions that XBPMs could be launched from submarines, deployed by SEALs, dropped from airplanes, and used on fleets of gliders.

Beyond military research, XBPMs are already being used in an environmental study of Bioluminescent Bay in Vieques, Puerto Rico. The bay, named for its rich marine life, is now deteriorating because of a surge of coastal construction. In the future, Fucile hopes that musters of XBPMs will be used routinely by scientists to make inroads into our now-sparse knowledge of bioluminescence.

—Lonny Lippsett

The Cacophony on the Coast

The Navy's deep-ocean acoustic detection methods don't apply in complex shallow waters

In the monotonous hush and uniform neatness of a library, it is quite possible to hear the soft echoes of a pin dropping many aisles away. But try it in the cluttered confines of a teenager's room, where a changing medley of music, cell phone rings, and television voices bounces off a jumble of strewn clothes, half-opened drawers, and scattered possessions.

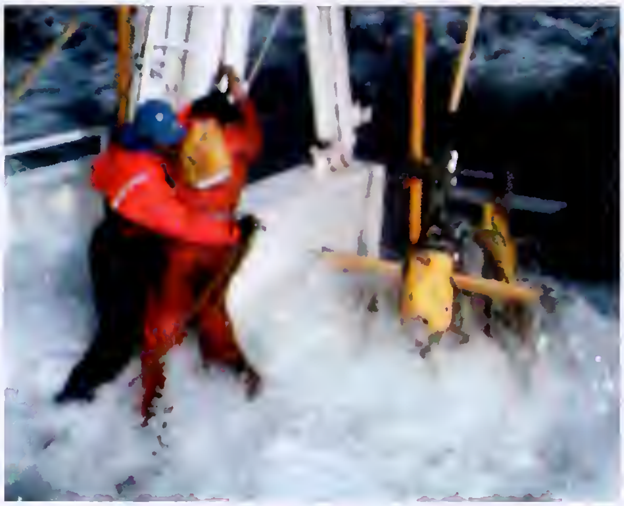
Unlike light, sound travels efficiently through water, and the Navy uses sound to monitor what's going on in the ocean. To understand the sound messages transmitted through the seas, you need to understand the medium through which they are transmitted.

Like a library, the deep ocean is a structured environment with a few basic, reliable rules about sound. To monitor Soviet submarines during the Cold War, the Navy exploited the SOFAR channel, a persistent deep-ocean water layer whose properties efficiently transmit low-frequency sound waves over vast distances.

But when the Navy shifted its focus to battle zones near the coast, it found that shallower, coastal waters are as noisy and chaotic as a teenager's room. In recent years, several WHOI researchers have participated in pioneering cruises aimed at examining the complicated behavior of sound waves in shallow-water regions.

A complex environment

In 1996-97, many WHOI researchers (including Glen Gawarkiewicz, Ken Brink, Frank Bahr, Robert Beardsley, Michael Caruso, and James Lynch) joined naval researchers to conduct the Shelfbreak PRIMER experiment, funded by the Office of Naval Research (ONR). They deployed arrays of instruments over a 40-square-kilometer (25-square-mile) area 96 kilometers (60 miles) south of Martha's Vineyard, where the relatively shallow continental shelf begins to slope steeply into the Atlantic abyss. Some instruments transmitted sound waves, while others listened for them. Still other instruments measured the characteristics of the watery pathways through which the sound waves propagated.



Arthur Newhall, WHOI

HANG ON—Amid large waves crashing onto the fantail, WHOI Research Specialist Frank Bahr (left) and the bosun of the R/V Endeavor *hold on to WHOI's SeaSoar surveying instrument—and each other—during a 1997 Navy-sponsored research cruise.*

Unlike the deep ocean, the structure of water masses near the coast is neither simple nor stable. Within the narrow confines of the continental shelf, fresh water from rivers and cold water from coast-hugging currents confront warmer, saltier, deeper water masses near the continental slope. These water masses remain distinct—flowing, changing, and rearranging themselves, not unlike cold and warm fronts in our atmosphere.

These coastal water masses drive strong currents along the shelf edge, which rearrange water temperatures over the outer shelf as they meander. Temperature gradients between warm- and cold-water masses can also be altered by spinning, independent water masses within the oceans—called eddies or warm-core rings—that often form at the edge of the continental shelf. Warm or cold air can also change coastal water temperatures over seasons or days. All these phenomena can change water properties and shift coastal oceanic fronts, which, in turn, scatter or distort sound waves in unpredictable ways.

Waves *within* the ocean

The irregular shape of the coastal seafloor adds another variable. Funded by ONR, WHOI and Navy researchers participated in the 2001 Asian International Acoustics Experiment in the East and South China Seas. As part of the experiment, WHOI researchers Keith von der Heydt and John Kemp designed and deployed an autonomous hydrophone array that recorded the longest, highest-quality shallow-water acoustics data set ever collected.

Analyzing the data, WHOI scientists John Colosi and Tim Duda found that as tides move over steep seafloor canyons and ridges in shallow waters, they generate internal waves. These huge ripples in the interior of the ocean, formed along the boundaries of different water masses, add yet another factor that complicates shallow-water sound propagation.

"The coastal ocean is a much more energetic environment than the deep ocean, and small day-to-day changes produce large complications," said WHOI physical oceanographer Glen Gawarkiewicz. Oceanographers have just begun to learn how to extract distinct and useful signals from the coastal noise.

—Lonny Lippsett

Robo-Sailors

Navy-sponsored research spawns a new generation of underwater vehicles

They look like torpedoes, but their mission isn't destruction.

In the mid-1990s, the Navy began funding research for small, robotic vehicles to perform unmanned reconnaissance in coastal waters. At WHOI, that helped spark the development of REMUS (Remote Environmental Monitoring UnitS), designed and built by Chris von Alt, Ben Allen, and colleagues in the Oceanographic Systems Laboratory.

Launched on pre-programmed underwater flight patterns and equipped with a changeable array of sensors, REMUS can map the seafloor or collect data on temperature, salinity, currents, phytoplankton abundance, and other seawater properties. The 5-foot-long, 80-pound vehicle can be launched and recovered by two people from a small boat, without a crane or special handling equipment. Easily programmed, REMUS can work alone for more than 20 hours before its batteries need recharging. It can travel at speeds up to 2.5 meters per second and to depths of 100 meters.

REMUS has proved a remarkable scientific tool, expanding researchers' ability to explore previously inaccessible regions. The Navy also gained a valuable tool: Sailors used several REMUS vehicles to detect mines in the Persian Gulf harbor of Umm Qasr in 2002. Navy officials said that each REMUS could do the work of 12 to 16 human divers, and the vehicles were "undeterred by cold temperatures, murky water, sharks, or hunger."

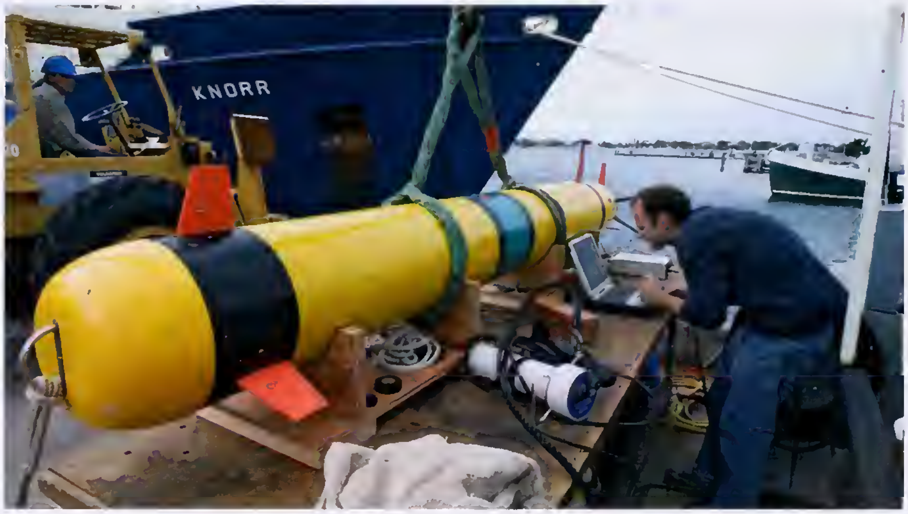
The Office of Naval Research also has funded Dave Fratantoni and colleagues at WHOI to develop another small, easy-to-deploy surveying technology—the glider. Gliders employ an internal displacement piston or an oil bladder to change their buoyancy. They now sink up to 200 meters (656 feet) in the ocean and then rise again to the surface, but vehicles under development will be able to dive ten times deeper.

Gliders fly in a saw-tooth pattern, measuring ocean properties and surfacing periodically to transmit data via satellite to scientists on ship or shore. They are slower than REMUS, but they can remain on the job for several months.

Valuable to the Navy, these new-generation undersea robots are also having productive non-military careers in the service of scientists exploring a wide range of ocean phenomena.

Brett Merrill, 3rd Mate, Bruce C. Heezen

GLIDER READY FOR TAKEIOFF—WHOI Research Associate John Lund worked with naval personnel aboard USNS Bruce C. Heezen *to deploy one of seven WHOI gliders used in an experiment in the western tropical Pacific Ocean.*



Tom Kleindinst, WHOI Graphic Services

UNDERWATER RECONNAISSANCE—WHOI Senior Engineering Assistant Greg Packard puts a REMUS 600 autonomous underwater vehicle through a series of pre-launch checks on the WHOI dock before it is tested in the waters near Woods Hole. Crane operator Doug Handy stands by. The REMUS 600 can carry a variety of sensors for underwater surveying and mapping and, not incidentally, can be deployed through submarine torpedo tubes.

Down on the Farm...Raising Fish

Aquaculture offers more sustainable seafood sources, but raises its own set of problems

By Hauke L. Kite-Powell, Research Specialist
Marine Policy Center
Woods Hole Oceanographic Institution

Imagine for a moment that the beef and poultry in your refrigerator came not from ranches and farms, but from the woods and prairies. Imagine that every pig, chicken, turkey, and steer was "free range," hunted from wild herds and brought to market. What would that mean to you as a consumer?

In the simplest terms, it would mean that your local supermarket would have higher prices and a less dependable and less plentiful supply of meat. The idea of abandoning our modern practice of raising livestock and harvesting all of our meat from the wild is absurd.

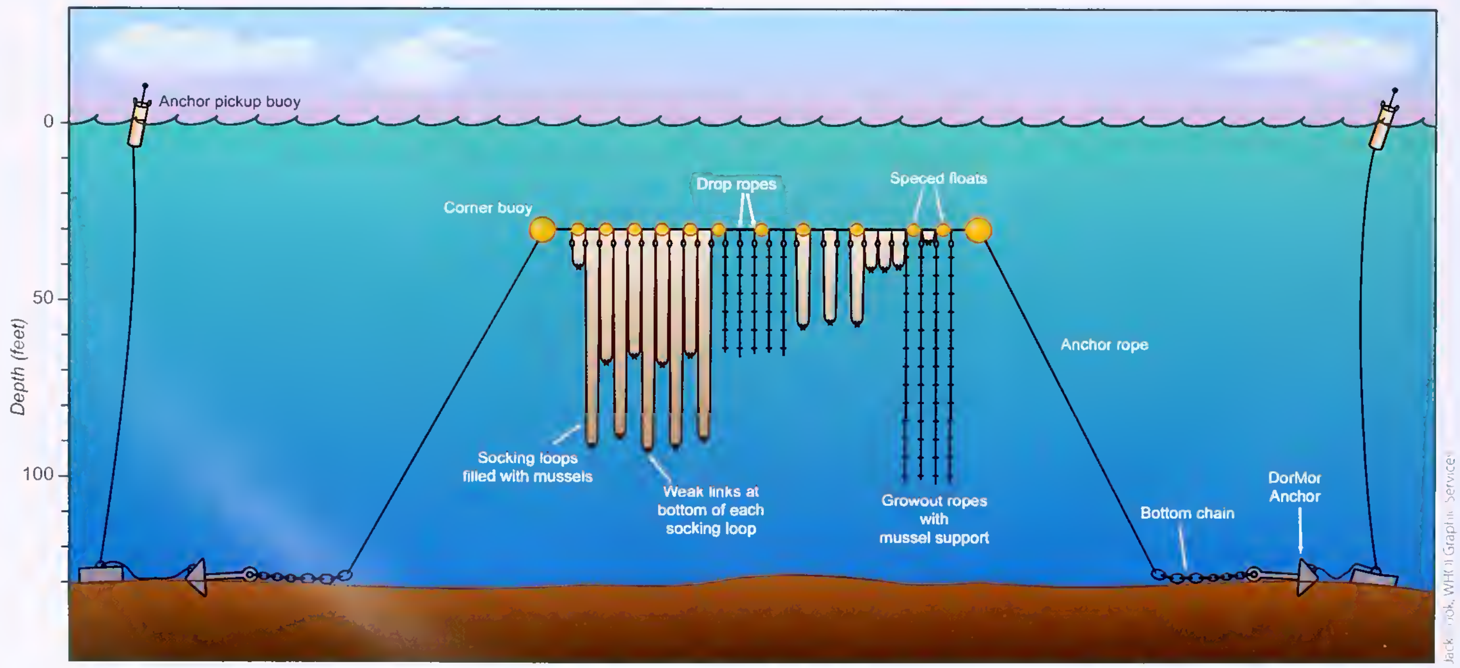
And yet that is exactly how we obtained most of our seafood until quite recently.

Aquaculture, or fish farming, is changing how we think about one of our main sources of protein. With many fish stocks shrinking due to overfishing or environmental degradation, aquaculture holds the promise of more reliable and more sustainable seafood production. The economic and social benefits could be significant for both consumers and producers.

But every benefit has a cost, and the costs of poorly executed aquaculture range from ecological damage to rampant disease in the cultured fish stocks. The financial costs of raising healthy fish also remain problematic in parts of the world. Current research is testing some solutions to these problems.

A new wave in the seafood industry

In 1950, about 20 million tons of fish were harvested globally, with nearly all of that catch coming from wild stocks in oceans, bays, lakes, and rivers. In the five decades since then, the world's population has tripled. Today, seafood production stands at 130 million tons per year, with one quarter of that total coming from aquaculture. About 20 million tons are farmed in freshwater facilities, 15 million tons in salt water.

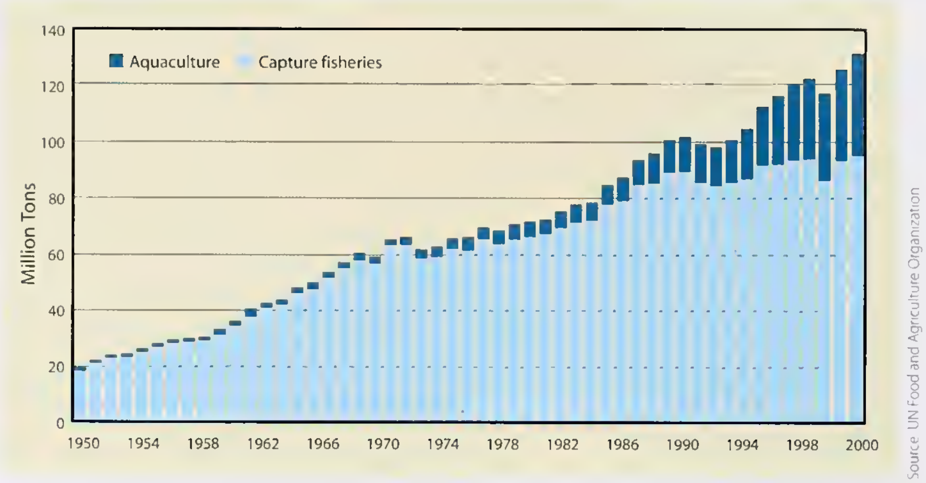


MUSSEL BUILDING—To study the feasibility of commercial shellfish farming offshore of New England, researchers from Woods Hole Oceanographic Institution created this demonstration system that grows blue mussels in the open ocean. The "longline mooring" uses submerged ropes and buoys to allow juvenile mussels to develop in nutrient-rich, naturally flushed waters.

Aquaculture first began to contribute significantly to world production in the 1970s, when it became clear that wild capture seafood harvests could no longer keep pace with the demand for fish. Many popular fish stocks had been overexploited even before that era, but the fishing industry compensated by repeatedly switching to previously "underutilized" species. By the 1980s, even diversifying the wild harvest could not increase the yield enough to feed the world's booming population and growing appetite.

Humans directly consume 75 percent of all seafood produced, with the remainder being processed into fish meal and oil for use in feeds for land animals and farmed fish. Thanks to the development of aquaculture—output has increased more than fourfold since 1985—the per capita supply of fish has remained roughly constant since 1970.

Seafood accounts for about 15 percent of the protein in the average human diet, about 16 kilograms per person per year. Residents of the United States, however, consume 7 or 8 kilograms per person, about half the global average. When they do eat seafood, few U.S. consumers realize that more than half of what they eat comes from fish farms.



WORLD CAPTURE FISHERIES AND AQUACULTURE PRODUCTION—Since 1950, both wild fish catch and farmed fish have increased significantly as the world population has tripled.

Developing countries outpace U.S.

By global standards, U.S. aquaculture production is relatively modest, with a value of less than $1 billion per year of the worldwide total of $50 billion. Catfish, salmon, and oyster farms dominate the U.S. efforts. Aquaculture development is constrained by economics, especially competition from low-wage foreign producers and a lack of available and affordable coastal real estate. As a result, the U.S. imports more than half of the seafood it consumes.

At the other extreme, China accounts for more than half of world aquaculture production, primarily through its large production of freshwater carp, the world's most plentiful aquaculture crop. (There are grounds for suspecting that the Chinese production statistics may be inflated.) Other significant crops include shrimp (tiger prawns) grown in coastal ponds, and seaweeds, oysters, mussels, and salmon grown in ocean cages.

Global aquaculture has focused on species that command a relatively high price. The freedom to select target species is greater for the fish farmer than for the wild capture fisher, and farmers have been selling their products for about $1.50 per kilogram, nearly twice the average price of wild capture seafood. That is good news for the developing world, where aquaculture can feed populations both directly and through income from exports.

Live fish are moved from shore-based aquaculture tanks and pens onto a boat for transportation to an open-ocean netpen.

Fish in a barrel

The most common technique for farming fish is pond culture, where fish are reared in shallow, earthen, open-air ponds that look like flooded agricultural fields. This method is mostly used to grow carp and other freshwater fish in Asia, shrimp in Latin America and Asia, and catfish in the southern United States. The simplest ponds are "self-contained" ecosystems in which fish feed on naturally occurring water plants. The density of fish stocked in these ponds is generally low—about 1 kilogram per cubic meter of water—but can be increased with investment in feed and in aeration systems that maintain oxygen levels in the water.

A higher stocking density can be achieved in ocean cage cultures (10 to 20 kilograms per cubic meter), where cages or "netpens" are anchored to the seafloor in open waters. This approach is often used for raising carnivorous marine species such as salmon. Natural currents remove waste products and maintain

Dale Leavitt, Roger Williams University

Walter Paul, WHOI

A NEW TYPE OF HARVEST—Left: Rigid cages are used to contain surf clams in a shellfish aquaculture demonstration experiment supported by Woods Hole Sea Grant. Adolescent clam "seedlings" are held in submerged cages until they grow to commercially viable size and weight. Right: Will Ostrom (blue hard hat), a senior engineering assistant in the WHOI Department of Physical Oceanography, and Joe Alvernes, a crewmember of the fishing vessel Nobska, *scrape mussels from a rope that had been submerged for 19 months.*

oxygen levels by continually replacing the water in the cages.

The highest densities are achieved in onshore tank farms, where up to 100 kilograms of fish are raised per cubic meter. These industrial style aquaculture methods use pipes, filters, and flushing systems to remove wastes and restore oxygen levels. Onshore systems rely on regular water exchanges—replacing tank water with fresh water from an external supply—or they circulate the tank water through systems of filters and other water quality systems.

Not as easy as it looks

Fish farmers and aquaculture researchers face a number of challenges as they attempt to expand aquaculture production. These include:

• ***Reproduction:*** To produce ever-larger quantities of fish in a sustainable way (that is, without further depleting wild stocks) and to obtain fish with optimal characteristics for farming, it is necessary to "breed" juvenile fish from specially selected captive stocks. But getting fish to reproduce consistently in captivity remains a challenge for many valuable species, such as tuna.

• ***Feed:*** There is no one-size-fits-all approach to feeding fish, and the optimal food for healthy growth is often species-specific. Farmers need feeds with ingredients that are economically viable, ecologically sensible, and healthy (free of contaminants) to the animals and consumers. For example, the farming of carnivorous fish such as salmon has been criticized for using excessive quantities of other fish in the production of feed. If the feed fish are plentiful and of little interest for human consumption, and if their fishery is managed properly, there shouldn't be a problem. But if not properly managed, these practices can contribute to overfishing of wild stocks.

• ***Disease management:*** As with cattle ranches, farming fish can lead to disease because parasites, viruses, and bacteria have a better chance of propagating in a densely packed population. Controlling disease presents its own problems. The excessive use of antibiotics and other agents can have negative effects on the environment and human consumers (for instance, repeated exposure to antibiotics can lead to immunity to such drugs).

• ***Genetics:*** Efforts to develop faster-growing fish through genetic manipulation are controversial, in part because escapees may affect wild stocks by competing or interbreeding.

• ***Waste disposal:*** Natural waste produced by the farmed animals, as well as excess feed, can result in an overabundance of nutrients in the areas around fish ponds or ocean farming areas. If this nutrient loading exceeds certain limits, it can encourage the excessive growth of algae and contribute to algal blooms. This ecological imbalance can culminate in eutrophication, the depletion of oxygen in the water to a point where it suffocates or drives away marine species.

• ***System design and economics:*** Engineers must design containment ponds and cages that can address these environmental issues while withstanding the forces of nature, doing all of it at a reasonable cost.

Many of these challenges come into play in two aquaculture ventures in very different settings where researchers from Woods Hole Oceanographic Institution (WHOI) have undertaken demonstration projects: the coast of New England and the island of Zanzibar off the coast of East Africa.

Yankee thrift and ingenuity

New England has a long association with fishing and seafood, not to mention one of the world's wealthiest populations. Seafood consumption in the region is below the global average, yet 25 percent higher than the U.S. average. Aquaculture production has been limited to mostly oysters and other shellfish, but the collapse of several traditional fish stocks, growing economic and regulatory pressure on fishermen, and an increasing reliance on imports has boosted interest.

There are several obstacles to aquaculture in New England. The first is the ready availability of low-cost seafood imports, which make it tough for local producers in this high-cost-of-living area to compete. The second is a shortage of affordable coastal real estate, both onshore and in nearshore waters, which makes coastal ponds and nearshore cage farming impractical. As a result, the future for this region appears to lie in high-density, onshore tank farming or in offshore, open-ocean operations focusing on high-end niche markets.

Before commercial aquaculture can begin in the open ocean, government agencies are going to have to develop a straightforward system for granting "tenure" to a piece of watery real estate. Depending on the location, several federal or state agencies may be involved in granting a permit for the installation of an offshore growout system. Even far from shore, conflicts can arise if a farm site is in or near established commercial fishing grounds, shipping lanes, or the habitat of protected species. In the long run, the nation may move toward a marine zoning system, much like that used onshore, to assign priority uses—fishing, shipping, recreation, or aquaculture—to parcels of ocean real estate.

Growing finfish or shellfish in open ocean waters also requires a significant engineering investment. Cages and other "growout" systems need to be able to survive the storms, choppy waves, and currents of the North Atlantic. Within the past decade, cage systems have been developed that can survive hurricane conditions (for instance, by submerging temporarily below the wave energy zone). Still, the economics of supplying and maintaining growout systems far from shore are only now being tested.

WHOI has undertaken one of these demonstration projects in the open waters of Rhode Island Sound, with support from the National Oceanic and Atmospheric Administration, the Sea Grant College Program, and the Massachusetts Department of Fisheries and Agriculture. Researchers and engineers are working to prove the technical and economic feasibility of growing blue mussels on ropes ("longlines") hanging from submerged buoys in deep water.

Early results from the New England demonstration projects are encouraging. During our first two-year experiment, hundreds of pounds of mussels were harvested from a single longline. Market-size mussels grew on the ropes in half the time they would take to grow in the colder waters north of Cape Cod. The equipment showed very little wear or damage, even though a hurricane passed through the area. Long-term success will depend on developing local markets that are willing to pay a premium for a reliable and consistent supply of fresh seafood, and on engineering to keep costs down.

Necessity and invention

On the island of Zanzibar, in the Indian Ocean off Tanzania, seafood is not a luxury but a means of survival. It is the dominant source of protein for the island's one million residents, who consume three to four times as much seafood as the average New Englander. As in the North Atlantic, many wild capture fish stocks are under intense pressure or depleted, and the catch today is half of what it was 20 years ago. But unlike New Englanders, the people of Zanzibar cannot afford to import fish. The per capita income is about $300 per year.

Aquaculture is critical for the food supply and for economic development of this

FARMING IN OPEN WATER—Researchers and commerical fishermen check on an open-ocean cage for finfish aquaculture in a demonstration project by the University of New Hampshire. The submersible cage is raised for feedings, cleaning, and maintenance, then lowered to allow the fish to develop in water that is naturally flushed by ocean currents.

Courtesy of the University of New Hampshire Open Ocean Aquaculture Program

Hauke Kite-Powell, WHOI

Hauke Kite-Powell, WHOI

UNDER AFRICAN SKIES—Aquaculture holds the promise of feeding the impoverished populations of some developing countries, while also providing a key crop for export. Left: Coastal fish ponds on the island of Pemba, Zanzibar. Right: Local fish farmers and researchers from the Zanzibar Institute of Marine Science use nets to haul in fish grown in the coastal ponds.

island. Zanzibar developed a successful seaweed farming industry in the 1980s, and that crop is now second only to tourism in the island's export trades. Seaweed is a source of carrageenan, a key ingredient in the cosmetics, manufactured foods, and pharmaceuticals industries.

This success has spurred interest in other kinds of aquaculture, such as pond farming of finfish and the addition of shellfish to the seaweed plots in coastal lagoons. Limited infrastructure—unreliable utilities and scarce materials—and the lack of a reliable source of juvenile fish have slowed these efforts. So, too, have concerns about environmental degradation from nutrient loading, which could threaten the island's vital tourism business.

With the technical assistance of researchers from Israel's National Center for Mariculture and from WHOI, and support from the German-Israel Fund for Research and International Development, the Lear Foundation and the McKnight Foundation, scientists in Zanzibar are developing a research and training infrastructure to meet these challenges. They have focused on pond culture using low-technology solutions, such as tidal flow instead of pumps for water exchange. They are working with "biofilters," using shellfish and seaweeds to remove excess nutrients from pond water before returning it to the sea. Cage culture experiments in protected nearshore waters are also being planned, and work is starting on a simple hatchery to provide juvenile fish for stocking. Researchers are also developing techniques to add shellfish farming to established seaweed plots.

Initial results from pond culture experiments are promising, and scientists on Zanzibar have begun to instruct would-be fish farmers in how to replicate the experimental farms. The hope is that farmed fish will soon increase the supply of seafood protein available to the residents of the island.

Beating hooks into plowshares

Aquaculture holds great promise, especially in developing countries and historically non-productive coastal areas with few natural wild fish stocks. Negative environmental effects from poor planning, design, and operating procedures have in some cases been problematic, but can be avoided through sensible regulation and monitoring. In the U.S., automation and other technologies will have to be harnessed to compensate for higher labor costs.

But from a global protein perspective, aquaculture is necessary. The question is not whether to farm fish, but how and where.

Karen Wilson

Hauke Kite-Powell studied naval architecture, marine engineering, policy, management, and economics at MIT, earning his bachelor's degree, two master's degrees, and a doctorate. His research interests include the economics and management of marine industries and resources, including maritime transportation, fisheries and aquaculture, and ocean observing systems. He first came to WHOI as a summer student fellow in 1985 and has conducted research full-time at the Institution since 1988. In addition to his research skills, he was officially admired by science buffs in 1997 when he was chosen as Mr. March for the "Studmuffins of Science" calendar developed by National Public Radio producer Karen Hopkin.

The Ocean Institutes

In 2000, Woods Hole Oceanographic Institution established four Ocean Institutes to accelerate advances in knowledge about the oceans and to convey discoveries expeditiously into the public realm. The Ocean Institutes' goals are to catalyze innovative thinking that can open up new scientific vistas, to spur collaboration among scientists in different disciplines, and to stimulate a rich and productive educational environment that will engage future leaders of oceanography. Concurrently, each Institute's mission is to shorten the time between acquiring knowledge and making it accessible to decision-makers who can use this information to benefit society and steward the Earth.

The Deep Ocean Exploration Institute investigates Earth's dynamic processes—beneath the oceans where more than 80 percent of all earthquake and volcanic activity occurs and where the clues to understanding the inner workings of our planet lie. The seafloor is our window into the dynamic, fundamental processes that generate natural disasters, produce oil and mineral resources, create and destroy oceans, rend continents, build mountains and islands, and foster life.

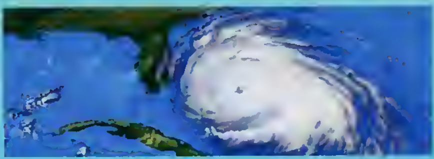
The Deep Ocean Exploration Institute:

- explores how our dynamic planet evolves and changes
- examines the basic forces that create earthquakes and volcanoes
- develops technology related to seafloor observatories and deep-submergence vehicles
- investigates unusual chemosynthetic communities of life on and below the seafloor
- explores potential new energy and mineral resources in the oceans

The Ocean Life Institute explores the ocean's extraordinary diversity of life—from microbes or whales—to identify ways to sustain healthy marine environments and to learn about the origin and evolution of life on Earth. The more we look into the oceans, the more we find remarkable life forms thriving in environments ranging from Antarctic sea ice to the volcanic crust below the seafloor.

The Ocean Life Institute:

- explores biodiversity in the oceans
- finds ways to monitor and sustain the health of marine ecosystems
- studies marine life's physiological and ecological adaptations
- investigates the evolution of life in Earth's oceans
- develops new techniques and instruments to explore ocean life



The Ocean and Climate Change Institute seeks to understand the role of the ocean in regulating Earth's climate and to improve our ability to forecast future climate change. The ocean stores vast quantities of heat, water, and carbon dioxide and works with the atmosphere in regulating global and regional climates—on time scales ranging from days (storms and hurricanes), seasons (monsoons), years (El Niños), to centuries and longer.

The Ocean and Climate Change Institute:

- identifies the climatic effects of ocean circulation patterns
- develops an ocean-monitoring network to forecast climate changes
- examines geological records to better understand ocean behavior
- studies ocean dynamics that may trigger large, abrupt climate shifts
- evaluates the ocean's response to the buildup of greenhouse gases

The Coastal Ocean Institute examines one of the most vital—and vulnerable—regions on Earth: the coast. Our planet's exploding population has put stress on the fragile coastal ocean and has exposed more people to coastal hazards such as storms, beach erosion, and pollution. Understanding the complex, delicately balanced processes at work in coastal areas is the key to ensuring that they remain productive and attractive.

The Coastal Ocean Institute:

- reveals basic processes underlying the coastal ocean's fertility
- provides sound science to guide coastal management policies
- examines uses of coastal resources, such as wind, oil, and fisheries
- identifies strategies to mitigate coastal hazards and natural disasters
- promotes awareness of the coastal zone's importance to society

Woods Hole Oceanographic Institution
Woods Hole, MA 02543 • 508-457-2000 • www.whoi.edu